the ground clip to each coupon, as described earlier, and repeating all of the measurements. These measurements are reported in detail elsewhere: but the key result is that while a significant difference is observed for the carbon coupon due to its very low resistance, no difference in current collection was observed for the germanium or Kapton coupons. If conduction through the material were important, a measurable enhancement would be expected. We believe, therefore, that our results point to what is primarily a plasma sheath effect.

Conclusions

The results reported here are the first experimental demonstration that the electrical properties of a solar array blanket can significantly impact the performance of the system. For the designer of real power systems, the relative importance of the two physical mechanisms discussed above may well be academic. Regardless of what is eventually shown to be the exact mechanism involved, it is clear that the use of weakly conductive blankets can lead to enhanced plasma current collection. This is true even if the material has what is normally considered to be a large resistance, as does the germanium coating reported here. This enhanced current collection appears as a power loss to the system and is obviously of importance to the designer.

The magnitude of the loss that a photovoltaic power system may expect to incur as a result of this effect depends on its design. In particular, spacecraft are generally grounded to the negative end of the solar array which means that the majority of the system, including the spacecraft structure, will float negative with respect to the plasma and therefore collect ions. As our data shows, ion collection is enhanced with weakly conductive coatings but, as is always true of ion collection, the absolute magnitudes are small and the overall effect may be negligible. The use of a negative ground with a high-voltage system, however, has serious implications for the final floating potential of the spacecraft? **as** has been amply demonstrated with Space Station Freedom (SSF). In the case of SSF, a plasma contactor had to be added to the baseline design to control potentially severe arcing and sputtering resulting from the grounding scheme. The final potential distribution on the solar arrays and structure resulting from the interplay of such a device with the power system is extremely complicated and beyond the scope of the present work, but we will point out that this is one case when large areas on the array can be driven to large positive potentials. Such a potential distribution will obviously also occur in the case of a positively grounded system. It is in such situations, however they occur, that our results will need to be considered and the use of such coatings carefully evaluated.

One research community affected by these results deals with atomic oxygen protective coatings. It was for this purpose that the germanium was initially added to the APSA coupon. Such coatings are not routinely tested for the effects we report and our results argue that they should be. For traditional low-voltage systems this may not be necessary, but for solar arrays which will operate in LEO at 100 V or more there is a clear potential for such coatings to lead directly to losses on the array.

Acknowledgments

All of the solar cell coupons used in this work as well as the flight versions for SAMPIE were fabricated for NASA by TRW Engineering & Test Division, One Space Park, Redondo Beach, CA.

References

[1] Hillard, G.B., and Ferguson, D.C., "The Solar Array Module Plasma Interaction Experiment: Technical Requirements Document," NASA TM-105660, May, 1992.

[2] Hillard, G. B., and Ferguson, D. C., "The Solar Array Module Plasma Interaction Experiment (SAMPIE): Science and Technology Objectives," Journal *of Spacecraft and Rockets* (to be published).

[3] Wald, L. W., and Hillard, G. B., "The Solar Array Module Plasma Interactions Experiment (SAMPIE): A Shuttle-Based Plasma Interactions Experiment," *Proceedings of the 26th Intersociety Energy Conversion Engineering Conference* (Boston, MA), Vol. 1, 1991, p. 385.

[4] **Kurland,** R. M., "Advanced Photovoltaic Solar Array Design," TRW Rept. 46810-6004-UT-00, TRW Engineering & Test Division, One Space Park, Redondo Beach, CA., Nov. 1986.

[5] **Hillard,** G. B., "Plasma Chamber Testing of APSA Coupons for the SAMPIE Flight Experiment," NASA TM-106084, **Jan.** 1993.

Ronald **K.** Clark
Associate Editor

Cercignani-Lampis-Lord Gas-Surface Interaction Model: Comparisons Between Theory and Simulation

M. S. Woronowicz*
ViGYAN, Znc., Hampton, VA 23666
and
D. F. G. Rault†
NASA Langley Research Center, Hampton, VA 23681

Introduction

IN recent years, many facets of physical modeling within the context of the direct simulation Monte Carlo (DSMC) method' have received increased attention. The general goal of this effort is to implement more sophisticated, realistic models for certain microscopic phenomena, without loss of accuracy at the macroscopic level, to increase the versatility of the DSMC method and to create greater confidence in the solutions produced by its users. One facet of this is the phenomenon of gas–surface interaction with incomplete momentum or energy accommodation.*

In dealing with this issue for a given study, investigators using DSMC generally assume diffuse reflection with complete momentum and energy accommodation, specular reflection (zero accommodation), or complementary fractions of each (Fig. 1). This basic model is called the "Maxwell" **model.**[3] Usually, an "accommodation coefficient" for some function of velocity $Q(V)$, denoted by σ_Q or α_Q, is defined as

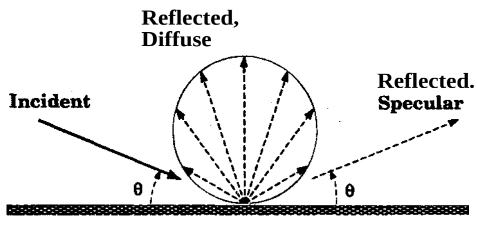

Fig. 1 Schematic representation of the angular distribution of gas molecules reflected from a solid surface for diffuse and specular models.

Received Sept. 1, 1993; revision received Jan. 6, 1994; accepted for publication Jan. 11, 1994.

*Research Engineer. Member AIAA.

†AeroSpace Technologist, Aerothermodynamics Branch, Space Systems Division. Member AIAA.

$$\sigma_Q \equiv \frac{\langle nQ|V\cdot\hat{n}|\rangle_{\text{in}} - \langle nQ|V\cdot\hat{n}|\rangle_{\text{out}}}{\langle nQ|V\cdot\hat{n}|\rangle_{\text{in}} - \langle nQ|V\cdot\hat{n}|\rangle_{\text{out,diffuse}}}$$

where n is the local number density, $\hat{n}$ is the surface normal, and the averaging occurs over allowable velocity space. Incomplete accommodation exists when σ_Q or α_Q is less than unity. Typically, the Maxwell model uses accommodation coefficients for tangential momentum σ_t, normal momentum σ_n, and translational energy *cy* as disposable paramenters.[3] However, data from many experiments show that the asymmetric, often multilobate, angular distribution of gas molecules reflected or re-emitted from solid surfaces under high-vacuum conditions is poorly represented by such a mnodel.[4] Although the inadequacy of the Maxwell model is readily acknowledged, it is widely used because it satisfies the principle of detailed balance, or reciprocity. Furthermore, the velocity probability distribution function (PDF) describing the state of reflected molecules is non-negative everywhere, and this PDF integrates to unity over allowable velocity space.[5]

A phenomenological model that has demonstrated some improvement over the basic Maxwell model, and that satisfies the criteria just described, was devised by Cercignani and Lampis (C-L) for monatomic molecules and analytically applied to various problems?" the C-L model is based on the definition of the accommodation coefficient, and it seeks to describe the reflected PDF based on the state of the incident molecules using reciprocity, normalization, and non-negativity as constraints. One result of the derivation for a monatomic gas is that only two distinct accommodation coefficients become disposable parameters. These are σ_t and the normal component of translational energy *cy*,. Completely diffuse or specular reflection occur in the C-L model when both coefficients are 1 or 0, respectively. For values of σ_t and *cy*, between these limits, reflected angular distributions of density and velocity moments become lobate, with preferred scattering tending toward specular reflection as σ_t and α_n approach zero. Recently, Lord described how to implement this model within the statistical DSMC framework.'

Although an increasing number of DSMC practitioners are incorporating the C-L model into their codes? no direct comparisons between C-L's analytical results and those using Lord's statistical implementation model have been performed. The purpose of this investigation is to provide some of those comparisons. One case supplements an earlier comparison between C-L results and an experiment by Hinchen and Foley for reflected angular density distributions of argon scattered off a platinum surface,[5,9] and the second compares DSMC results with Lord's implementation against C-L results for free molecular flow over a flat plate.[6]

Molecular Beam Scattering

Hinchen and Foley[9] investigated the scattering of collimated beams of noble gases at various angles of incidence from a platinum (Pt) surface. The effects of varying gas and surface temperatures were measured, as well as the effect of preparation of the Pt surface? Published results included angular density distributions of the scattered gas molecules in the plane of the incident beam? Cercignani and Lampis revisited this problem analytically for the particular case where a collimated beam of argon (Ar) at 22°C was scattered from a Pt surface at 808°C, and incident beam angles varied from 15 to 45 deg? For these conditions, they were able to match the experimental results over the range of incidence angles with a single set of accommodation coefficients (σ_t, *a,*) = (0.1, 0.3).

Cercignani and Lampis modeled the incident beam as monoenergetic, although a more realistic description for the collimated beam should permit a distribution of energy levels? In order to compare Lord's statistical implementation with C-L theory, the following results also pertain to a directed, monoenergetic source. All that was required computationally was to keep track of the reflected distribution of simulated monatomic molecules scattered from a surface using Lord's description of the scattering kernel, with the constraints that each incident molecule had precisely the same set of translational velocities. The resulting angular distributions of 10^7 reflected molecules in the plane of the incident beam are presented in Fig. 2, along with our calculated analytical solution using the C-L model. Hinchen and Foley's data are included

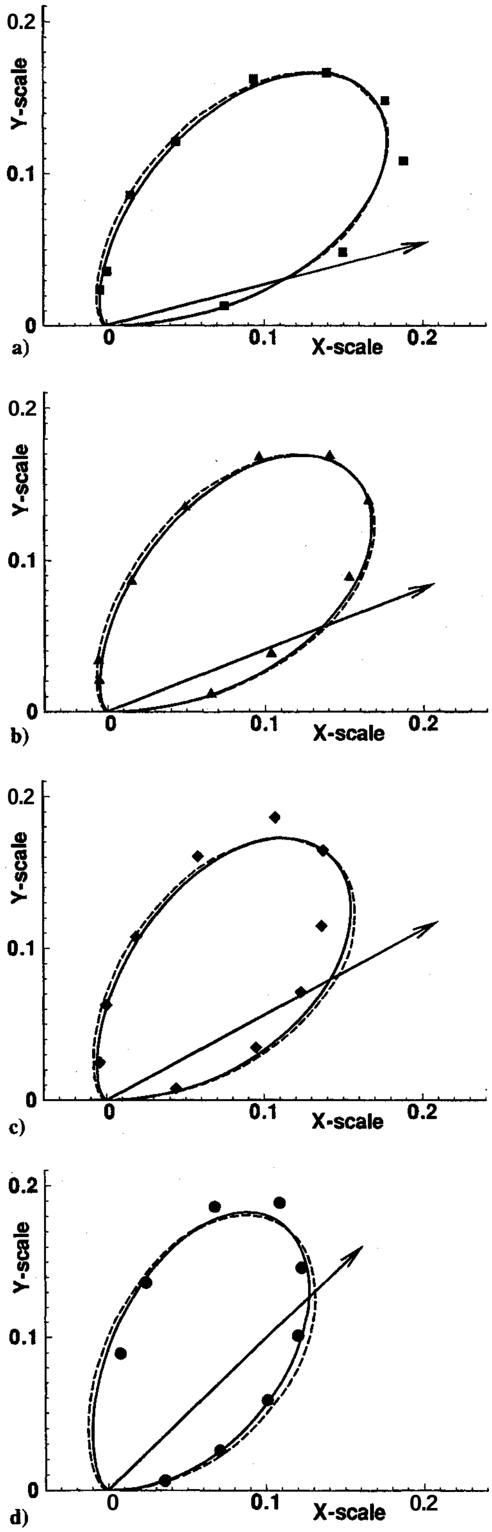

Fig. 2 Angular density distribution of 22°C Ar scattered off a 808°C Pt surface in the incidence plane. Comparison between theoretical C-L model (solid lines), Lord's statistical implementation (dashed lines), and experiment (symbols) for α_n = 0.3 and σ_t = 0.1. Beam incidence angle = a) 15 deg, b) 22.5 deg, c) 30 deg, and d) 45 deg. Arrows denote specular reflection angles.

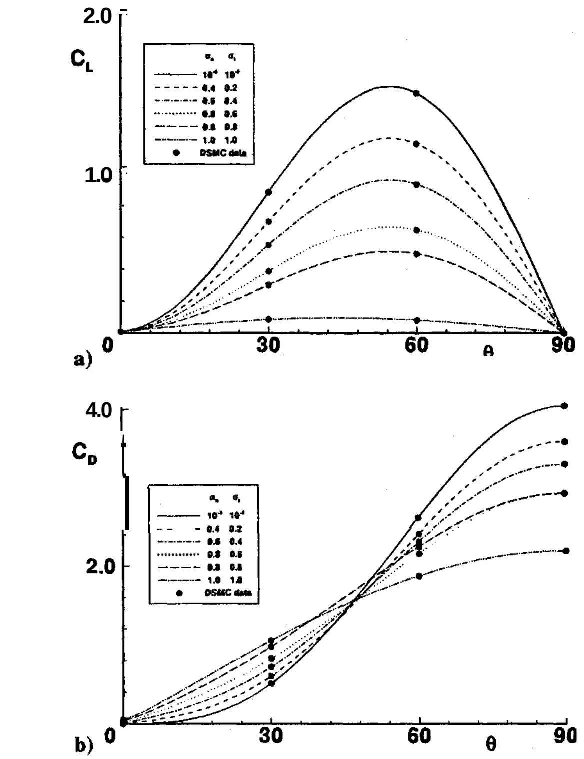

Fig. 3 Aerodynamic force coefficients for an inclined flat plate in free-molecule flow, $S_\infty = 10$, $T_\infty/T_s = 1$, 0 deg ≤ 8 ≤ 90 deg. Comparison between C-L theoretical results and Lord's statistical implementation for a) C_L and b) C_D versus 8.

to reproduce the information depicted in Fig. 17 of Ref. 5, and the specular reflection angle is included to help orient the reader. Because there was no sound procedure to scale the experimental, analytical, and simulated results, all three distributions have been scaled arbitrarily, in order to observe the relative variations between different sets of results. The level of agreement between the analytical and simulated results is very close. Slight discrepancies between the two may be caused by inaccuracies in the numerical implementation of the analytical calculations and the effects of averaging over small ranges of angles in the simulated results. In addition, the statistical analysis relies heavily on the computer's random number generator.

Free Molecule Flat Plate

Cercignani and Lampis analytically incorporated their gas–surface interaction model into free molecule theory to create some rather complex expressions describing lift and drag coefficients for flow of a monatomic gas over a flat plate? They then explored the' effects of various parameters on the behavior of these coefficients for single- and double-sided plates inclined at angles of attack θ ranging from 0 to 90 deg.

We endeavored to duplicate their results for flow over a single-sided plate with freestream speed ration $S_\infty = V_\infty/\sqrt{2RT_\infty} = 10$, surface temperature T_s equal to freestream temperature T_∞ and arbitrary values for σ_t and a, between 0 and 1. Lord's implementation replaced the standard Maxwell model in a version of Bird's G2 DSMC code,[10] and intermolecular collisions were disallowed. The plate was placed alongside one of the computational boundaries in the DSMC simulation to expose only one side to the flow. Simulations were run for these conditions at θ = 0, 30, 60 and 90 deg for each set of accommodation coefficients listed in Fig. 9 of Ref. 6, which are tabulated in Figs. 3a and 3b. Although we obtained a full set of flowfield solutions for each application, we were mainly interested in DSMC estimates for lift and drag coefficients. Figure 3 shows excellent agreement for values of lift and drag coefficients between theory and simulation for all 24 runs.

Conclusions

It appears from this investigation that Lord's statistical implementation of the C-L model, indeed, faithfully reproduces ana lytical results. This is encouraging becasue the C-L model, although phenomenological in origin, provides a physically more realistic description of incomplete gas–surface accommodation at the microscopic level than does the standard Maxwell model. It would be desirable to create a database of surface accommodation coefficients within the C-L framework for realistic gas–surface pairings at energy levels consistent with rarefied environments encountered by objects considered for investigation.

Acknowledgments

M. S. Woronowicz was supported by NASA Contract NAS1-19237. The authors appreciate R. Gordon Lord's helpful suggestions.

References

[1] Bud, G. A., ***Molecular Gas Dynamics and the Direct Simulation of Gas Flows,*** 1st ***ed.,*** Clarendon, Oxford England, UK, 1994, pp. 1–445.

[2] **Bird,** G. A., "Low Density Aerothermodynamics," AIAA Paper 85-0994, June 1985.

'Hayes, W. D., and Probstein, R. F., ***Hypersonic Flow Theory,*** 1st ed., Academic, New York, 1959, pp. 396–398.

[4] **Hurlburt,** F. C., "Gas/Surface Scatter Models for Satellite Applications," ***Thermophysical Aspects of Re-entry Flows,*** edited by J. N. Moss and C. D. Scott, Vol. 103, Progress in Astronautics and Aeronautics, AIAA, New York, 1986, pp. 97–119.

'Cercignani, C., ***The Boltzmann Equation and Its Applications,*** 1st ***ed.,*** Springer-Verlag. New York, 1988, pp. 104–137.

[6] **Cercignani,** C., and Lampis, M., "Free Molecular Flow Past a Flat Plate in the Presence of a Nontrivial Gas–Surface Interaction," ***Journal of Applied Mathematics and Physics (Zeitschrift für Angawandte Mathematik und Physik),*** Vol. 23, Dec. 1972, pp. 713–728.

'Lord, R. G., "Application of the Cercignani-Lampis Scattering Kernel to Direct Simulation Monte Carlo Calculations," ***Rarefied Gas Dynamics,*** edited by A. E. Beylich, 1991, pp. 1427–1433.

'Carey, V. P., "Stochastic Modeling of Transition Regime Heat Transfer for a Cylinder in a High-speed Gas Flow," AIAA Paper 93-0726, Jan. 1993.

[9] **Hinchen,** J. J., and Foley, W. M., "Scattering of Molecular Beams by Metallic Surfaces," ***Rarefied Gas Dynamics,*** Vol. 2, edited by J. D. de Leeuw, 1966, pp. 505–517.

"Bird, G. A., ***The G2/A3 Program System Users Manual,*** Version 1.7, March 1991.