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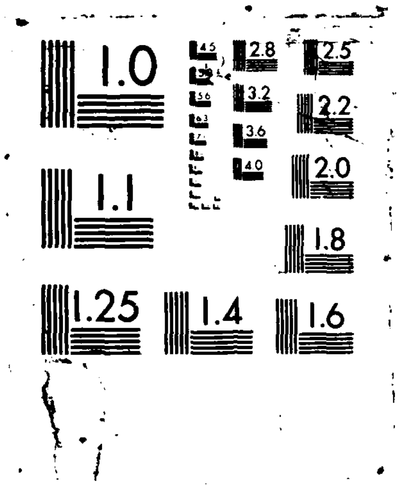
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Final Report
for the period
September 1986 to
December 1987

Nozzle Lip Effects on Gas Expansion into the Plume Backflow Region

February 1988

Authors:
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FOREWORD

This final report documents the Air Force Astronautics Laboratory (AFAL) in-house study of nozzle lip effects on gas expansion into the plume backflow region. AFAL Project Manager was Dave Weaver.

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The Direct Simulation Monte Carlo technique has been used to investigate the detailed flow structure in the region near the lip of a nozzle flowing to vacuum. The results for a range of nozzle lip thicknesses and shapes for argon are presented.

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Introduction

The expansion of rocket nozzle gases into a low density background is an important problem with application to spacecraft contamination and heat transfer, IR sensor interference, and high altitude rocket plume signature analysis. The expansion of gases around the nozzle lip and into the region upstream of the nozzle exit plane, usually referred to as the backflow region, is a particularly complex gas dynamic problem. It has been recognized for many years (Refs.1-6) that the expansion of the subsonic and lower Mach number supersonic regions of the boundary layer around a nozzle lip can produce significant flux into the high angle backflow region not predicted by the conventional Prandtl-Meyer uniform supersonic flow analysis. The small thrusters used for attitude control on various spacecraft usually have high expansion ratios, and therefore contain large boundary layers that can produce particularly large fluxes into the backflow region. It has recently been recognized that nonequilibrium effects (Ref. 7), due to the rapid rarefaction of the nozzle flow exiting to vacuum or near vacuum, can affect the structure of the flow around a nozzle lip. Consequently, accurate modeling of the flowfield around a nozzle lip and into the high angle backflow region cannot be obtained using standard equilibrium gas dynamic models. The Direct Simulation Monte Carlo (DSMC) modeling technique (Ref. 8), which models a gas flow by following some representative number of molecules through simulated collisions, does account for nonequilibrium effects and is essentially the only technique presently available for accurate prediction of these flows.

The shape of the nozzle lip may play an important role in determining the flux into the backflow. Pipes et al. (Ref. 9) observed some effects of nozzle lip shape on the flow field at the exit plane of carbon dioxide and nitrogen expansions from small nozzles, with a pronounced dependence of the effect on the level of condensation in the flow. Direct evidence of lip shape effects on flow into the backflow region was observed by Chirivella (Ref. 10) for pure nitrogen flows. Hueser et al. (Ref. 11) used the DSMC technique to study the detailed flow field around the nozzle lip for conditions simulating the IUS motor at 282 km altitude. They found large differences between the flowfield predicted by the DSMC technique and that predicted by the equilibrium Method of Characteristics technique. They used a finite size nozzle lip, which was found to have a significant effect on the local flow field, but they used only one shape for one set of initial flow conditions. A detailed theoretical analysis of the effects of different lip shapes on the flow field around the lip of a nozzle with zero half angle (tube) will be presented in this report. Future efforts will investigate the effects of upstream conditions (density, temperature, gas mixtures) and nozzle half angle, on the flow field around the nozzle lip, and experimental work is ongoing to provide verification of the calculations.

Model Description

The DSMC method, developed by G. A. Bird (Ref. 8), models the gas flow by following the trajectories of a large number of simulated molecules within a region of simulated space. The basic assumption in the method is that the molecule movement can be decoupled from the collisional process. A probabilistic rather than a deterministic method is used for calculating collisions, and is therefore restricted to dilute gas flows in which the mean spacing between molecules is large compared to the molecular diameter. The time parameter in the model corresponds to physical time in the real flow. All calculations are unsteady, but steady flow may be obtained as the large time average of the unsteady flow conditions. The basic assumptions used in the DSMC technique are the same as those in the Boltzmann equation, so that the results are equivalent to a numerical solution of the Boltzmann equation as long as the time step, cell size, and the number of simulated molecules are kept within reasonable limits. The art of setting up the calculation is in defining these "reasonable" limits. A DSMC calculation in many ways is more like an experiment than a traditional analytical analysis. The primary labor is in creating the proper controlled and defined conditions that do not produce any unexpected biases in the results.

The results presented here were obtained using a two-dimensional DSMC code written by G. A. Bird running on an Apple Macintosh computer upgraded to a Levco Prodigy 4, which runs at about the same speed as a VAX 11/780 minicomputer.

The first case investigated theoretically is the flow of argon into vacuum through a 2-cm long tube of 2-mm radius for rectangular tube lips with various wall thicknesses from 0 to 1.2 mm. Due to the extremely large change in gas number density from the internal flow to the far backflow region, the calculations are conducted in four steps (Fig. 1). The first uses VNAP2, a finite-difference Navier-Stokes solving code, to calculate the internal flow to a position 2-mm upstream of the tube exit plane. The Monte Carlo code is then used to calculate the flow from that position to a position 0.15 mm from the tube exit plane. The influence of the wall thickness on the flow at this start line was checked and was found to be negligible. The third step is a full Monte Carlo calculation from the start line 0.15 mm inside the tube out into the forward flow and around the lip into the backflow region. The run is allowed to proceed until good statistics are obtained in the region directly in front of the lip (~48 hours), but not long enough to produce good statistics in the backflow region (7-8 days). The final step is a calculation of the flow from a horizontal line along the bottom edge of the lip out into the backflow region (Fig. 1), using the results of step three for the input start conditions at that line. Again, the influence of the lip thickness on the start line conditions was checked and found to be negligible. Consequently, the same start line was used for all lip thicknesses. This final step typically required 70-80 hours for a large enough number of samples to be produced in the backflow region to obtain smooth distributions of the flow parameters.

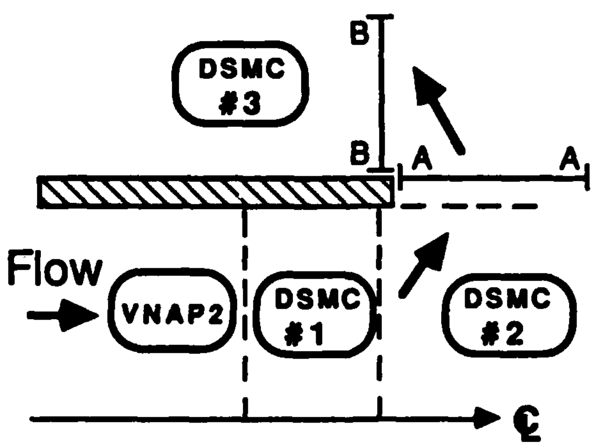

Figure 1. Calculational Regions. Dotted Lines Show Boundaries of Calculation Region. A-A and B-B are Longitudinal and Radial Profiles Presented in Figures to Follow.

A second set of cases was investigated using the same tube dimensions and stagnation conditions, but with a "knife edge" shaped lip of various thicknesses (Fig. 2). The angle of the lip edge was kept constant (53.13°) for each lip thickness. A full region (from 0.15 mm inside the tube) Monte Carlo calculation was run until good statistics were obtained for the region in front of the lip. Separate runs were then made for each lip thickness using a start line at the bottom edge of the lip obtained from the results of this full run, as was done for the squared off lip cases.

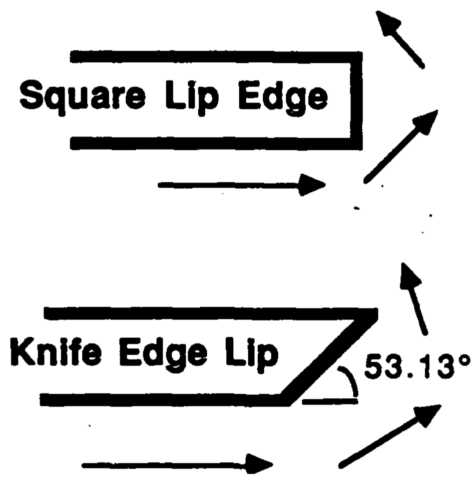

Figure 2. Lip Shapes.

The cell structure used (Fig. 3) was the final configuration reached after a number of iterations. The mean free path must be at least 2-3 times greater than the cell size to avoid flow smearing, and the mean collision time must be 2-3 times greater than time step for the calculation to accurately track changes in the flow parameters. The cells were adjusted so that the flow field and cell structure met or exceeded these criteria in all cells except for those cells far from the lip in the forward flow region, where the mean free path was slightly less than the cell diameter. The flow field is slowly varying in those regions, so that no flow smearing is expected due to these low ratios.

Results

All of the results to be presented here are for argon from a stagnation condition of T=300 K and P=1 kPa (7.5 torr). Diffuse reflection (full accommodation) of gas particles from the tube walls was used for all the calculations shown. A strong boundary layer develops for these conditions (Re ~500 at tube end) and fills a large portion of the tube at the exit plane, as illustrated in Fig. 4,

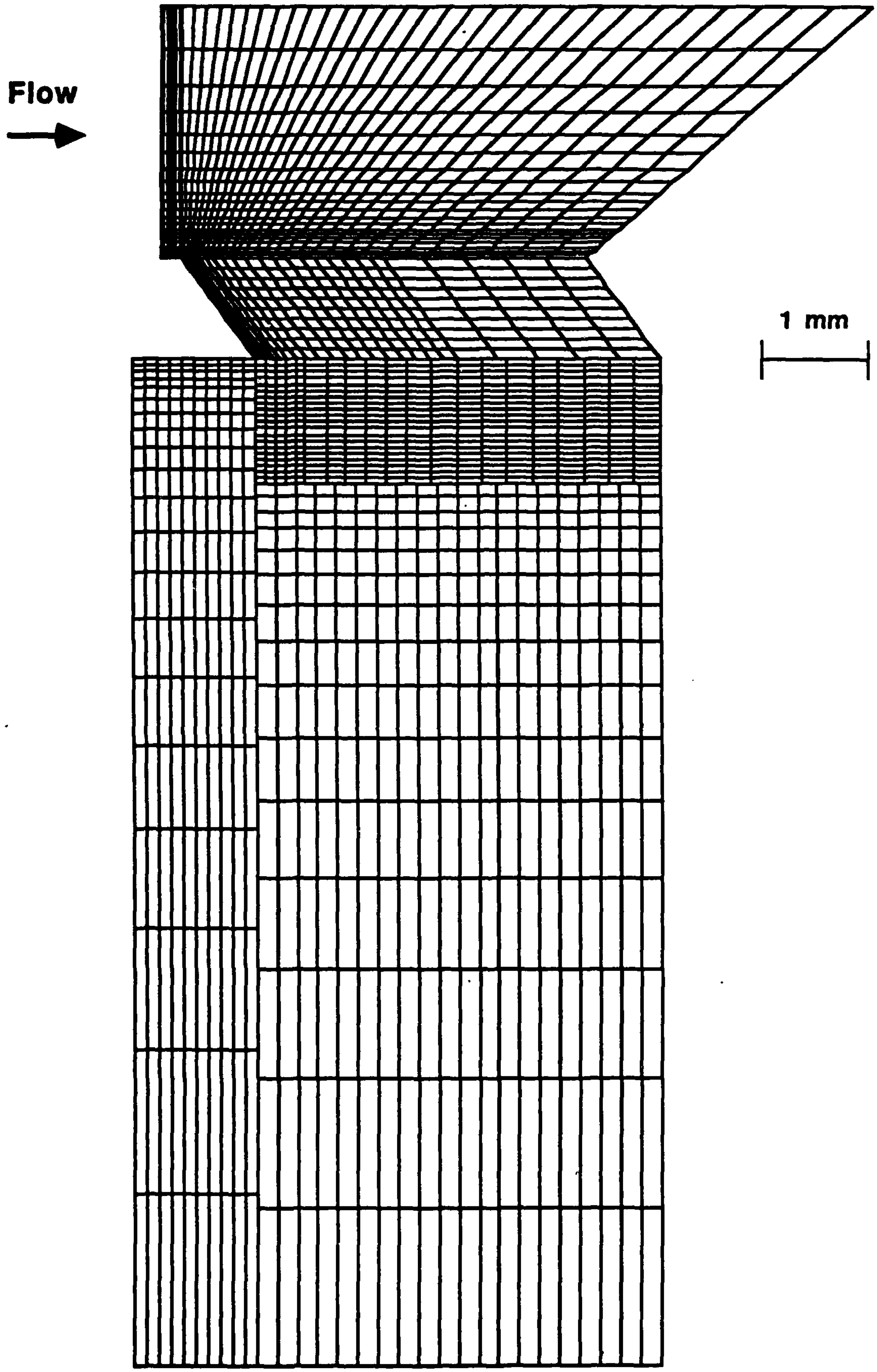

Figure 3. Cell Structure. Cells Directly in Front of Lip Are Too Small to be Resolved.

where the Mach Number and temperature profiles at the nozzle exit plane are shown.

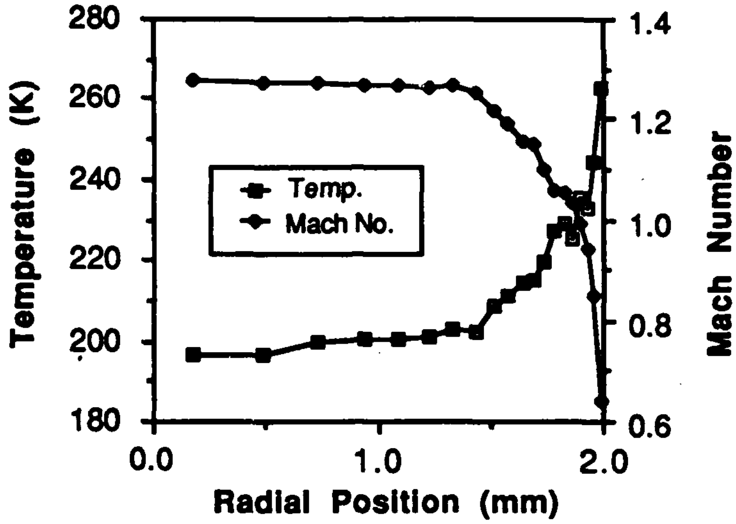

Figure 4. Temperature and Mach Number Profiles at Tube Exit Plane.

One measure of the effect of lip shape and thickness is the total amount of flux into the backflow region. In Fig. 5 the flux of argon passing through a plane perpendicular to the tube wall at the tube exit plane, and out to a distance of 8 mm from the outside tube wall is shown (profile B-B in Fig. 1).

Both tube thickness and tube lip shape have pronounced effects on the backflow flux. The drop in the flux appears to be linear for the square lip for 0.2 to 1.2 mm thick lips. For the knife edge lip, the drop appears to be linear for 0.5 to 1.2 mm thick lips. From these results it can be concluded that the scattering off of the front face of the lip has a significant effect on the gas flux into the backflow region.

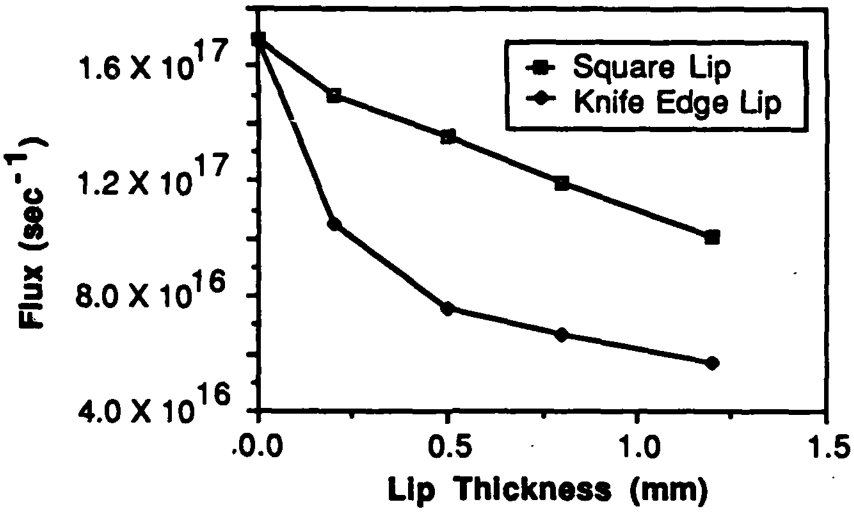

Figure 5. Flux Into Backflow Region Dependence on Lip Shape and Thickness.

The complete flow field number density distribution is shown in gray scale format in Fig. 6 for the 0.8 mm square lip, and in Fig. 7 for the 0.8 mm knife edge lip. Only the flow in front of the lip and into the backflow is presented since the forward flow region is identical for the two cases. Rarefaction is very fast near the outer edge of the lip for both cases. The flow for the knife edge lip expands more slowly in front of the lip, but faster around the outer lip edge than the square lip. This is illustrated more clearly in Fig. 8, where a horizontal profile of the number density along a line at the position of the lip's top edge is shown (profile A-A in Fig. 1). The number density for the knife edge lip is much greater than that for the square lip out to a distance of about 4 mm from the wall, at which point the the lip shape no longer influences the flow field.

Despite the much larger number density in front of the lip for the knife edge, the total flux into the backflow region is much lower for the knife edge than for the square lip (Fig. 5). The reason for this is illustrated in Fig. 9, where the flow angle is shown along the horizontal line at the top of the lip (profile A-A). The flow angle is much lower for the knife edge lip, which results in more of the flow being directed in the forward direction (<90°) for the knife edge lip than for the square lip.

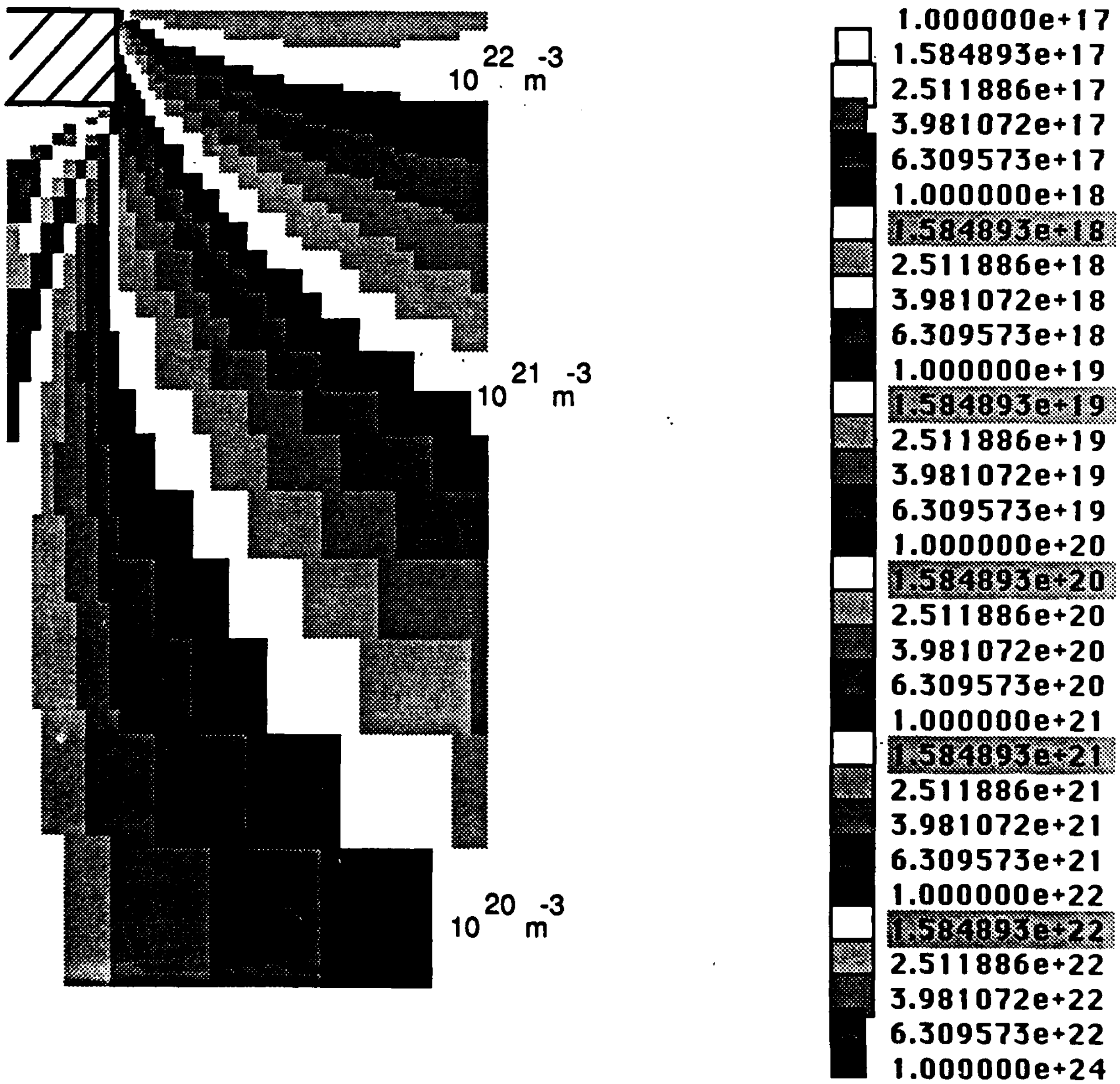

Figure 6. Number Density Distribution for Square Lip. Log Scaling is Used.

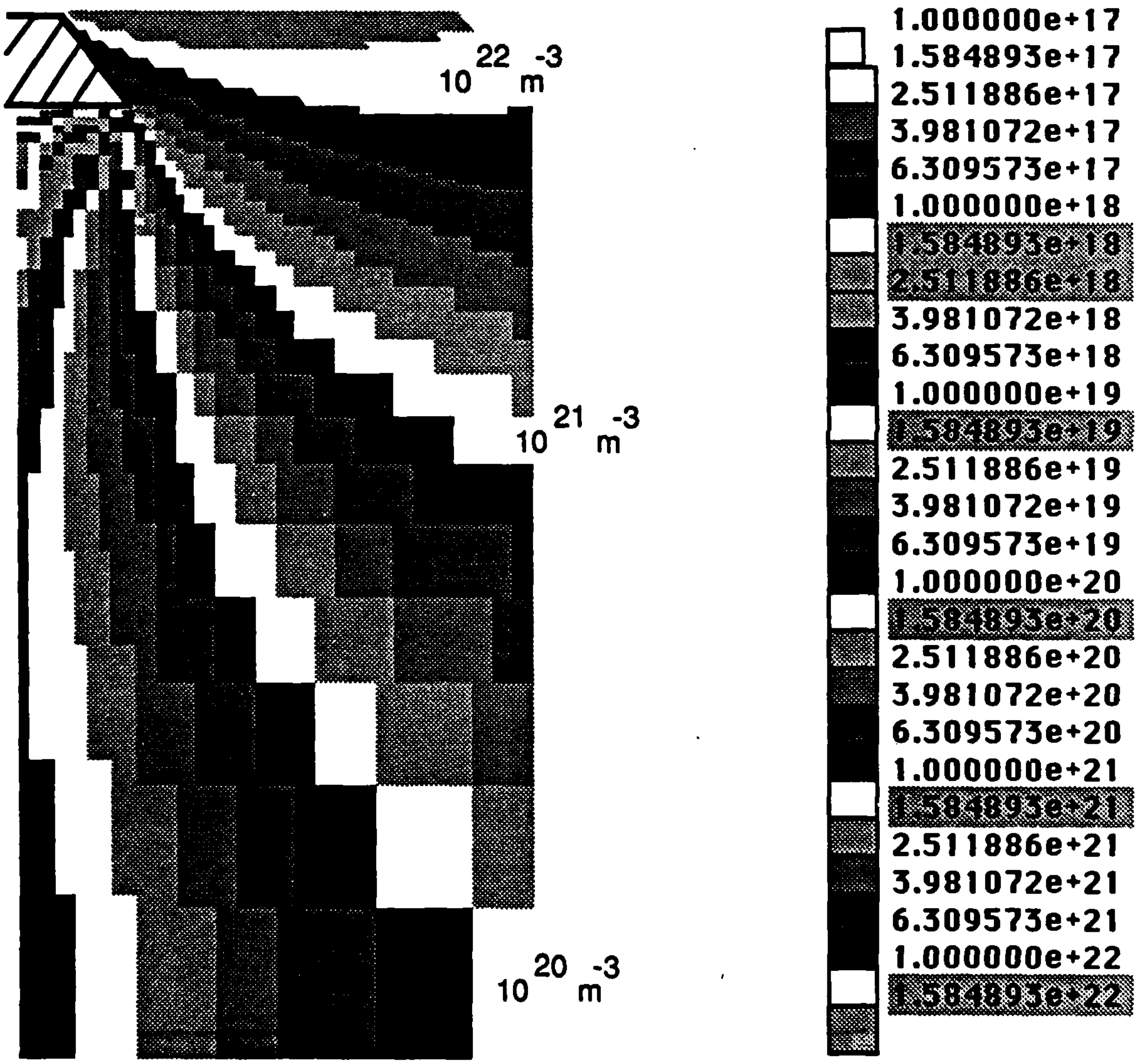

Figure 7. Number Density Distribution for Knife Edge Lip. Log Scaling is Used.

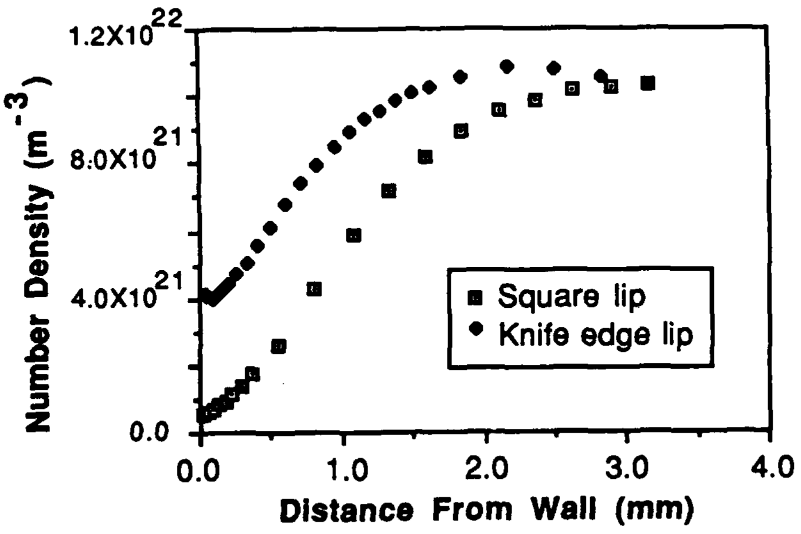

Figure 8. Number Density Profile at Top of Lip for 8-mm Thick Lip.

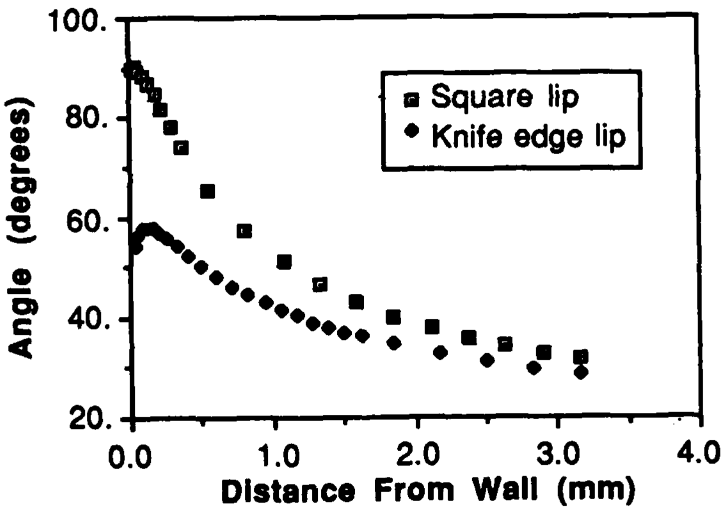

Figure 9. Angle Profile at Top Edge of Lip for 0.8-mm Lip.

A more detailed look at the flow field into the backflow region is shown in Fig. 10 for the square lip. The unit flux (gas particles per m^2 per second) of argon gas into the backflow at the exit plane peaks at a position within 1 mm of the wall, with the peak position moving farther out as lip thickness increases. The value of the unit flux drops significantly near the wall as the lip thickness increases. At large distances from the wall the unit flux converges to a constant value. A similar picture was found for the knife edge lip.

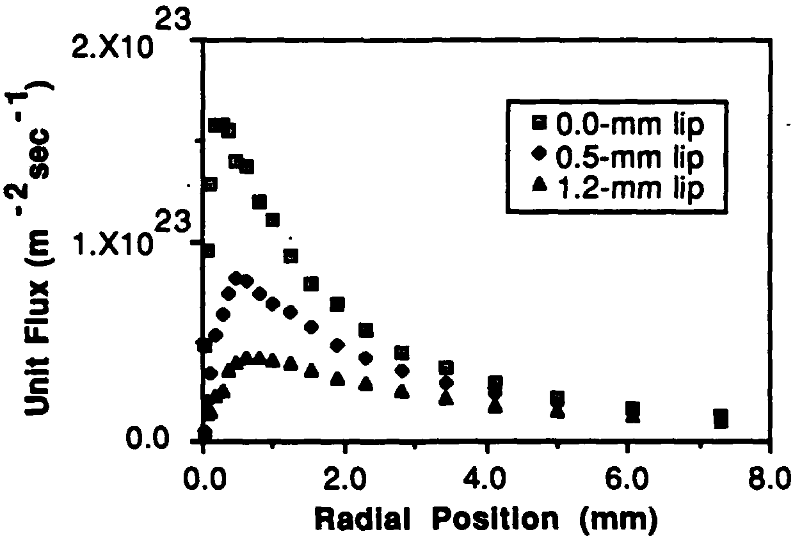

Figure 10. Unit Flux at Exit Plane in Backflow Region.

The other parameter of critical importance to the physical phenomenon of interest in the backflow region is the flow angle, which will determine the flow field far from the nozzle lip region. The flow angle in the backflow region at the exit plane for the square and knife edge lips is shown in Fig. 11. The expansion around the square lip produces a flow with a much lower angle than that for the knife edge lip for the section of the flow within a millimeter of the outer tube wall. At large distances, the angle of the flow converges for all lip thicknesses and shapes.

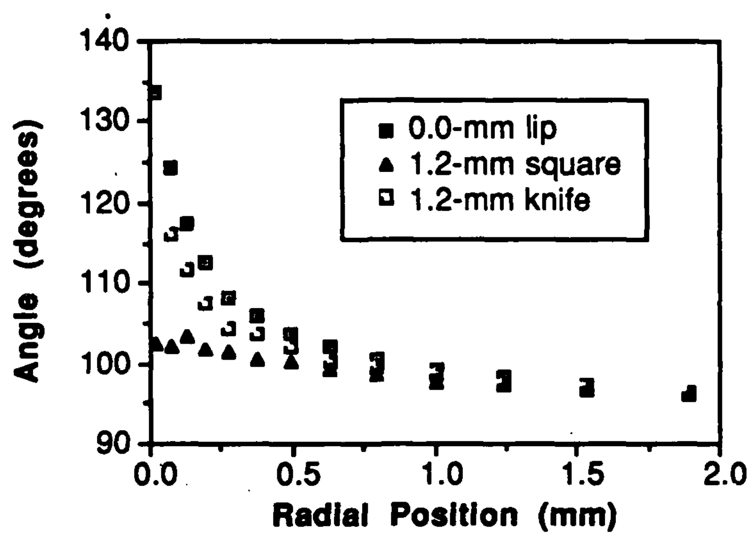

Figure 11. Flow Angle in Backflow Region at Exit Plane.

The ratio between the total flux into the backflow region for the knife edge and square lips at various lip thicknesses is shown in Fig. 12. This illustrates that the reduction of backflow flux due to the knife edge lip increases with overall lip thickness up to around 0.5 mm, at which point the ratio between the flux for the square lip and knife edge lip is constant. One might therefore conclude that by employing a knife edge lip, it is possible to reduce the backflow flux by a factor of about two, and consequently reduce potential spacecraft contamination by a similar factor. Unfortunately, total flux is only one parameter contributing to the potential for contamination or other unwanted effect. In Fig. 13 we illustrate the quantitative difference between the flow angle at the exit plane in the backflow region for the square and knife edge lips. For the thicker lips, the angle near the wall is larger for the knife edge lip than it is for the square lip, despite the fact that the flow angle in front of the lip starts out at a much lower value for the knife edge lip (Fig. 9). For the knife edge case the expansion is more like the zero thickness lip, which, as we have seen (Fig. 11), produces higher angled flow than thicker lips. Depending on the particular phenomenon of concern, this increased angle may counter any benefit gained from the decreased flux of knife edge lips compared to square lips.

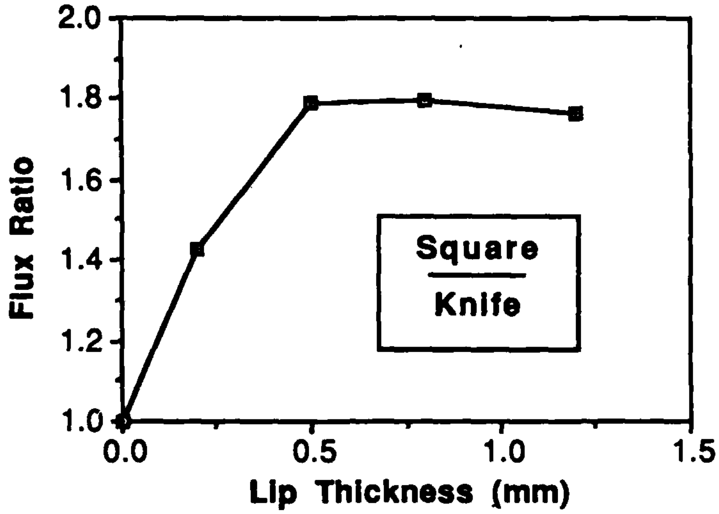

Figure 12. Flux Ratio Comparison for Knife Edge and Square Lips.

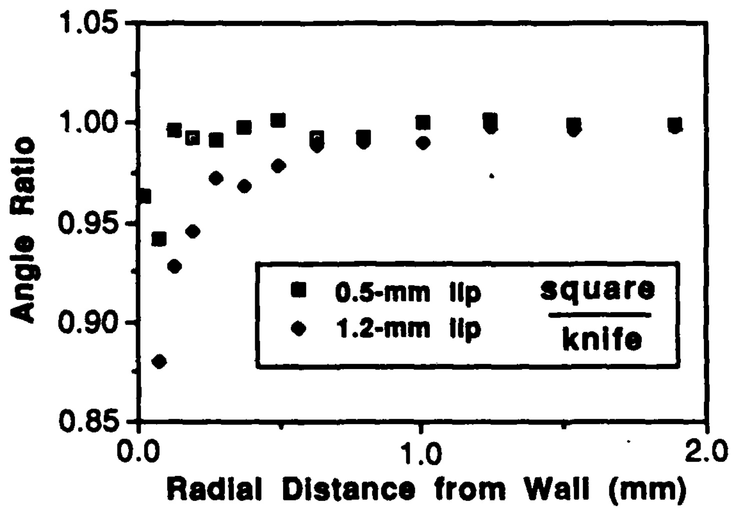

Figure 13. Angle Ratio Comparison for Knife Edge and Square Lips and Two Lip Thicknesses.

Summary and Conclusions

The structure of the argon flow through a 4-mm diameter tube, around the tube lip, and into vacuum has been investigated using the DSMC technique.

Two cases, a squared off lip and a knife edge lip, have been compared and the results show that the shape and thickness of the lip have a significant influence on the flow field. It can be concluded that the collisional interaction of the gas with the front face of the lip makes a major contribution to the resulting flow characteristics into the backflow region.

It must be emphasized that the results presented in this report are for a single monatomic gas flowing to pure vacuum with no background gas interactions. In the actual cases of interest, there will always be some background gas moving at high velocity with respect to the emitted plume flow, which may be made up of a number of different molecular weight species. Consequently, any conclusions with respect to spacecraft contamination or plume radiation processes must wait for a more complete modeling effort which includes background gas interactions, which can be quite large, (Ref. 12) as well as the effects of gaseous separation of the various species as they expand around the lip. (Refs. 11,12) In addition, direct comparison to experimental data will also be necessary before these types of calculations can reliably be used to predict the structure of the backflow for actual rocket nozzles.

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