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MOLECULAR GAS DYNAMICS APPLIED TO LOW-THRUST PROPULSION

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SUMMARY

The Direct Simulation Monte Carlo method is currently being applied to study flowfields of small thrusters, including both the internal nozzle and the external plume flow. The DSMC method is employed because of its inherent ability to capture nonequilibrium effects and proper boundary physics in low-density flow that are not readily obtained by continuum methods. Accurate prediction of both the internal and external nozzle flow is important in determining plume expansion which, in turn, bears directly on impingement and contamination effects.

INTRODUCTION

An important consideration in placing small electric thrusters on satellites is the effect the plumes may have on contamination and heating of solar arrays, instrumentation and other subsystems, as well as disturbance torques that may be induced by impingement on various spacecraft surfaces. Assessment of interactions between the spacecraft and thruster requires an accurate description of the expanding plume from the nozzle using the appropriate fluid dynamic models.

The current work is specifically directed at applying gas dynamics on the molecular level to the phenomena associated with viscous flows in nozzles and plumes of small electrothermal thrusters, such as arcjets and high-temperature resistojets, designed for satellite stationkeeping and attitude control. Of particular interest is the prediction of plume expansion, especially in the off-axis region where the plume may impinge on spacecraft surfaces. A continuum code based on the Navier-Stokes' equations is also applied, with the results used to scale the grid and provide inflow conditions for the molecular model.

In prior work,[1,2] the flow of nitrogen in and from a nozzle was computed with two numerical techniques: one based on continuum theory that numerically solved the Navier-Stokes equations for compressible flow,[3] and one based on a stochastic model of kinetic theory that used the direct-simulation Monte Carlo (DSMC) method pioneered by Bird[4] and modified by Boyd.[5] Each was applied to solution of a low-density, viscous gas flow in a converging-diverging nozzle of conical shape that simulated flow in a resistojet. This work demonstrated that the numerically intensive DSMC technique could be applied readily to a low-density nozzle flow, where the flow varied from continuum at the throat to rarefied at the exit plane and also demonstrated that results from the DSMC method matched well with experimental measurements of Pitot pressure and flow angle made in the plume.

The DSMC code developed by Boyd is employed in the current study to assess the effect of nozzle shape on plume expansion and surface impingement. Nozzles of conical, trumpet, and bell shapes are considered with flow rates of nitrogen at 6 mg/s and helium at 2.4 mg/s. The nozzle geometries and flow conditions are given in Tables 1 & 2. To demonstrate the utility of DSMC to predict potential impingement effects and to assess the validity of a semi-empirical model commonly used for impingement analysis, comparisons are made of density contours produced by the DSMC code with those obtained from Simons' method.[6]

THE DSMC METHOD

The DSMC code applied in this study simulates the flowfield in two-dimensional, axisymmetric coordinates and utilizes the VHS gas model for determination of collisional cross-sections. Rotational energy exchange is computed with the probability model of Boyd.[7] The flows are assumed to be both chemically and vibrationally frozen.

The computational grids used in the current study are based on continuum flowfield solutions from RKRPLUS.[8] The mesh for the nozzle flow consists of 250x88 cells and 800,000 particles are used in the simulation. The nozzle flow simulation begins just downstream of the throat, in the diverging section, and uses results from the continuum code for the inflow surface. The performance of the DSMC code on a Cray/YMP for this case is 1.08×10^{-6} CPU seconds/particle/time step.

The nozzle and plume flows are simulated separately due to the large variation in density between the two regions. A mesh consisting of 130x96 cells is used for the plume simulation with 48 particles per cell. An inverse-squared relation for density with distance from the nozzle exit plane is used to scale the cell dimensions. The plume simulations require 14.4×10^{-6} CPU seconds/particle/time step on an IBM RS/6000 workstation.

SAMPLE OF RESULTS

Isograms of Mach Number are given in Fig. 1 for the internal flow of nitrogen for each of the three nozzle shapes. The nozzles have the same exit-to-throat area ratio of 225:1 but differ in length because of the contour. The figure illustrates the distinct flow structure of each shape. The conical shape gives the maximum expansion contrasted to the bell contour, derived from the classical Rao design methodology, that restricts expansion of the flow to the point of causing viscous deceleration from a maximum Mach Number of about 6 in the internal portion of the nozzle to a Mach Number of about 5 at the exit plane.

To quantify differences in plume expansion for the various nozzle shapes, density contours along arcs of various radii originating from the center of the exit plane are given in Fig. 2. The curves are normalized by the density on the plume axis (0^o) for each case. In Fig. 2a (arc radius = one exit dia.) the density for the trumpet nozzle is higher than for the cone and bell nozzles. The effect of nozzle contour on plume shape, however, diminishes with arc radius as is readily apparent by the similarity of the curves in Fig. 2b (arc radius = 5 exit dia.).

Comparison of density contours for the conical nozzle from the DSMC method with the Boynton-Simons' model[6] for the expansion of the nozzle core flow are compared in Fig. 3 along a radial line 30° off the plume axis extending from the centerline of the nozzle exit plane to 0.1 m into the plume. The Boynton-Simons' model predicts a plume density about an order of magnitude higher than the DSMC simulation.

CONCLUSIONS

The DSMC technique is a practical tool for prediction of nozzle and plume flow, and assessing the effect of plume expansion on surface impingement for small thruster nozzles characterized by low-density, highly viscous flow. The prediction of plume density from the DSMC method for the conical nozzle of this study is substantially lower than from the widely used Boynton-Simon model. As the results are preliminary and significant, they will be investigated further in continuation of this work.

REFERENCES

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Table 1: Nozzle Geometries

	Cone	Trumpet	Bell
Throat Diameter	0.635 mm	0.635 mm	0.635 mm
Exit Diameter	9.526 mm	9.526 mm	9.526 mm
Area Ratio, (A/A^*)	225	225	225
Exit Half-Angle	20°	40°	10°
Diffuser Length	12.301 mm	12.301 mm	16.04 mm

Table 2: Nozzle Flow Conditions

Propellant	Nitrogen	Helium
Flow Rate	6.0×10^{-6} kg/s	2.4×10^{-6} kg/s
Total Pressure, P_o	9100 Pa	10360 Pa
Total Temperature, T_o	294 K	297 K
Wall Temperature	298 K	298 K
Throat Reynolds Number	700	250

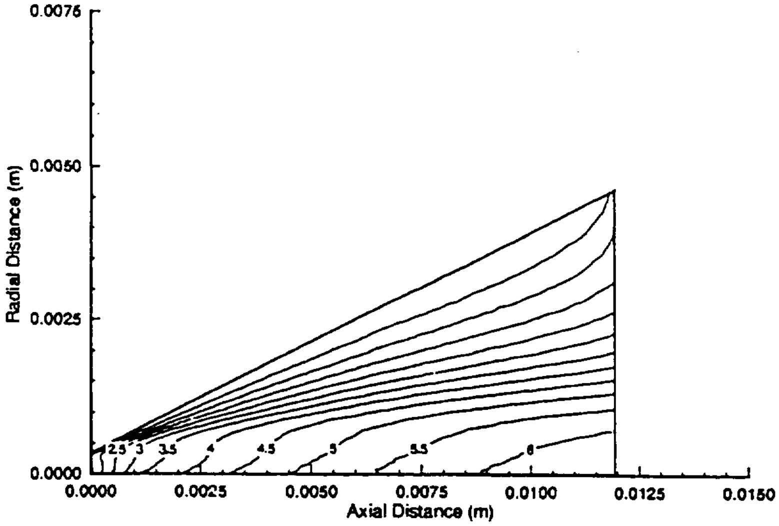

Fig. 1a. Mach no. contours of N_2 flow through conical nozzle

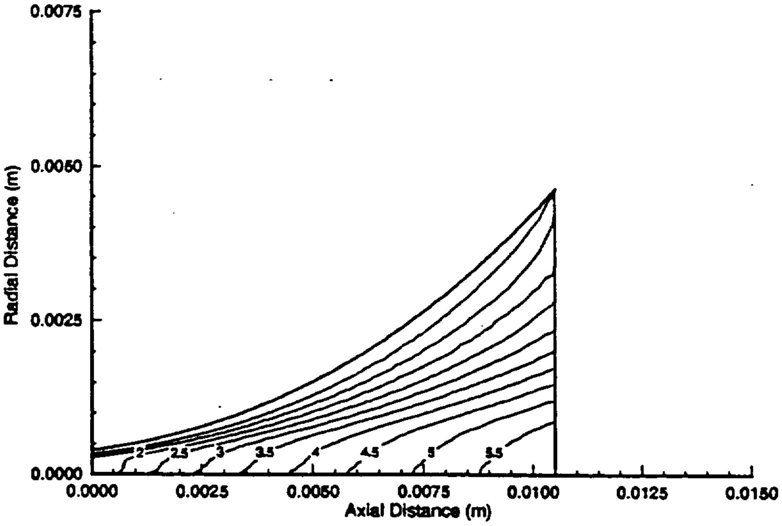

Fig. 1b. Mach no. contours of N_2 flow through trumpet-shaped nozzle

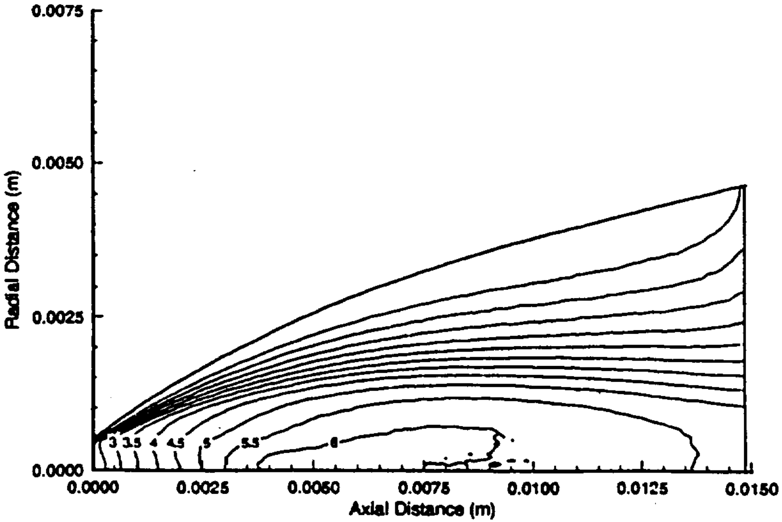

Fig. 1c. Mach no. contours of N_2 flow through bell-shaped nozzle (short)

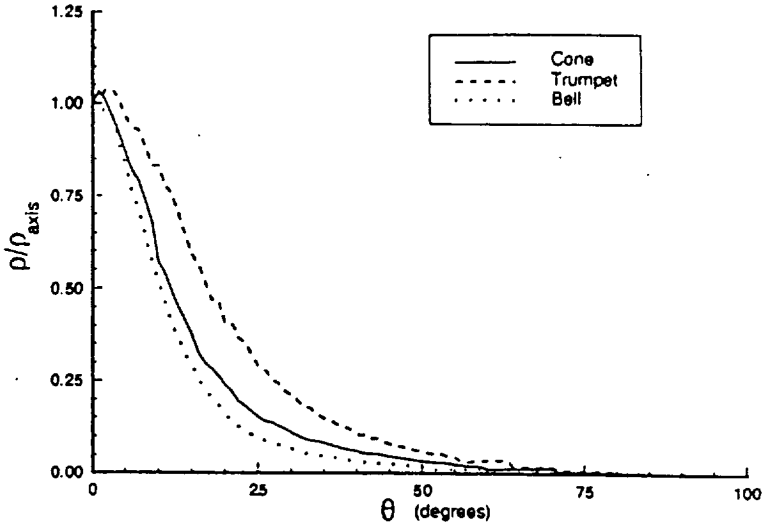

Fig. 2a. Normalized density vs. theta at arc radius = 1 exit diameter

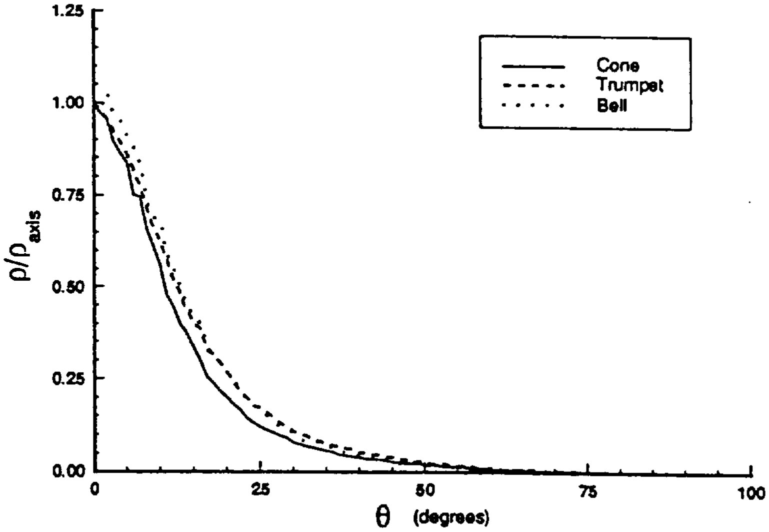

Fig. 2b. Normalized density vs. theta at arc radius = 5 exit diameters

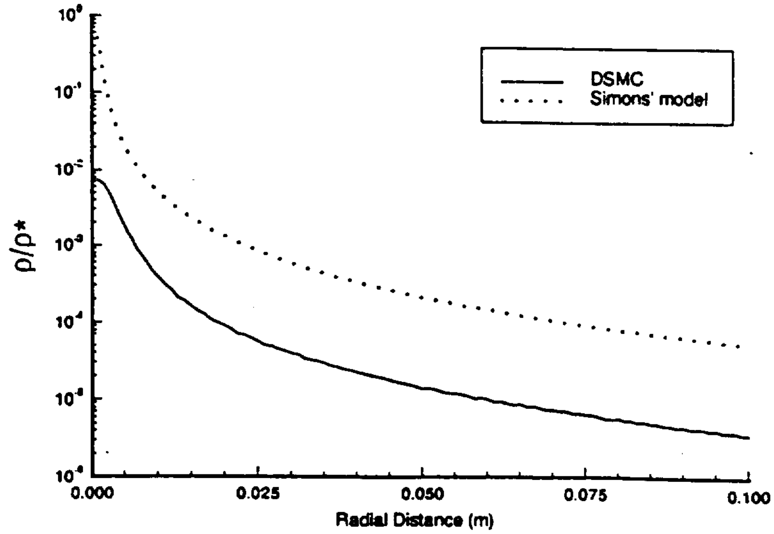

Fig. 3. Normalized density vs. radial distance at theta = 30°