droplets penetrating into the airstream do not burn in DIM, its fuel consumption ratio is slightly smaller than that predicted by DRM. As compared to experimental observations, where droplet combustion was observed outside of the gas-phase combustion zone for large-droplet sprays,[1] DRM and DIM gave better qualitative descriptions of the spray combustion modes than did DEM, with DIM providing the most detailed gas-flame configuration.

For D_{30} = 100 μm spray, the fuel consumption ratio predicted by DEM is substantially lower than those predicted by DIM and DRM, with that predicted by DRM being higher than that predicted by DIM in the upstream region of the combustor. The spray combustion modes predicted by DRM and DIM, droplets with envelope flames outside of the main gas flame for large droplet sprays, are in agreement with experimental observations, while that predicted by DEM, a broader diffusion flame enclosing vaporizing droplets, is not. Note, however, that for a polydisperse spray, where mean droplet size is large, there exist droplets that are too small to be ignited. This explains why the fuel consumption ratio is overpredicted by DRM in the upstream region. Considering this aspect of spray combustion modes, DIM does give more appropriate predictions. On the other hand, DEM underpredicts the fuel consumption ratio as much as 20% at the middle part of the combustor because it fails to predict droplet burning, which is a significant combustion mode for large droplet spray.

Conclusions

Three droplet combustion models, including DEM, DRM, and DIM, have been evaluated for spray combustion through a qualitative comparison of their predictions with experimental observations. The three models accurately predict the experimentally observed spray diffusion flame for small droplet spray, giving similar global combustion performances. For large droplet sprays, DRM and DIM predictions, droplets with envelope flames outside of the main gas flame, remain in agreement with experimental observations, while DEM predicts a diffusion flame without droplet combustion. In addition, DEM predicts a lower combustion performance in comparison to those predicted by the other two models. DRM accurately predicts droplet combustion for large-droplet sprays, but overpredicts the combustion performance of a polydisperse spray, with the predicted gas-flame falsely excluding multidroplet combustion of small droplets. DIM is able to effectively model an adequate flame configuration, something the other two models fail to do. For large-droplet sprays, DIM successfully predicted single droplet combustion of large droplets, multidroplet combustion of small droplets, and external group combustion. Among the three models, it may be concluded that DIM is the most accurate model for spray combustion. For an even more realistic prediction of spray combustion, the droplet ignition criterion in DIM should include the effects of transient droplet heating and surrounding convective flow; work that is currently in progress.

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Measurement and Analysis of a Small Nozzle Plume in Vacuum

P. F. Penko*
NASA Lewis Research Center, Cleveland, Ohio 44135
I. D. Boyd†
Cornell University, Ithaca, New York 14852
and
D. L. Meissner‡ and K. J. DeWitt§
University of Toledo, Toledo, Ohio 43606

Introduction

THERE is continuing development of small thrusters that operate on electrical power for both primary and auxiliary satellite propulsion. As a part of this development, a study is in progress to gain a better understanding of thruster-satellite interaction and design considerations in placing electric thrusters on satellites. Of particular interest is the prediction of thruster-plume expansion, especially in the off-axis region where the plume may impinge on spacecraft surfaces. The problem is being approached numerically, by modeling the nozzle flow and plume on both the continuum and molecular level, and experimentally by making plume flowfield measurements in a vacuum facility.

In prior work,[1] the flow of nitrogen in a nozzle was computed with two numerical techniques. One, based on continuum theory, numerically solved the Navier-Stokes equations for compressible flow. The other, based on a stochastic model of kinetic theory, used the direct-simulation Monte Carlo (DSMC) method. 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

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*Aerospace Engineer, M/S SPTD-1. Member AIAA.
†Professor of Aerospace Engineering. Member AIAA.
‡Graduate Student; currently with Owens Illinois, Toledo, OH.
§Professor of Chemical Engineering. Member AIAA.

the exit plane. Furthermore, the DSMC results were successfully validated by experimental measurements made in the near field of the plume. The same DSMC method was also evaluated successfully for expanding flows in the far-field plume of a helium thruster.[2]

Other investigators have performed similar measurements on small control thrusters. Legge and Dettleff[3] made pitot pressure measurements in the plume of a small hydrazine thruster to an axial distance of 100 mm. Lengrand et al.[4] obtained density and rotational temperatures using an electron beam in the plume of a nitrogen thruster to an axial distance of 240 mm. More recently, Jafry and Vanden Beukel[5] made mass-flux measurements in the plume of a helium microthruster to a distance of 140 mm. For the current investigation, the measurement distance in the plume is nearly double that of the maximum extent reported in these previous studies, extending to 480 mm in the axial direction, and 60 mm in the radial direction. The unique nature of this extended test area allowed evaluation of the numerical method for very rarefied flow conditions.

Experimental Apparatus

The experimental work for this study was conducted in a large vacuum facility and is described in Ref. 1. The experimental apparatus used in the facility simulated flow in a resistojet, and is also described in Ref. 1 where it is referred to as configuration 2. The nozzle was of conical shape with an exit diameter (*De*) of 31.8 mm, and an exit-to-throat-area ratio of 100:1. The vacuum system maintained a facility pressure of about 2×10^{-2} Pa for a nitrogen nozzle flow of 6.8×10^{-5} kg/s. The traversing mechanism used for measurements in the nozzle plume had a range of 8.8 nozzle diameters in the radial (*R*) direction, 15.1 nozzle diameters in the axial (*Z*) direction, and 360 deg in rotation. The measurement area was confined to the forward portion of the plume where pressures in the flow were within the minimum sensing range of the instrumentation.

Measurement Probes

Pitot tubes of 1- and 6.4-mm diameter, connected to capacitance manometers, were used to measure pressures in the

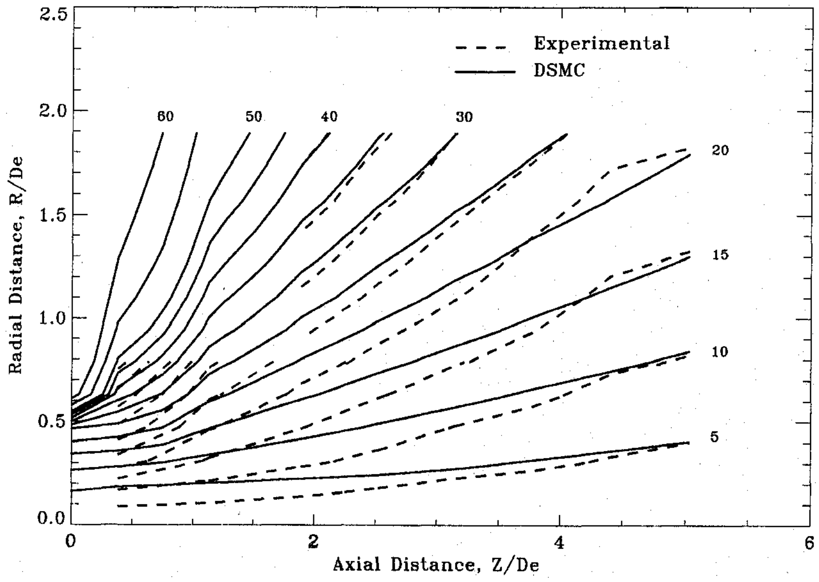

Fig. 1 Comparison of flow-angle contours computed with the DSMC method and measured with the conical probe.

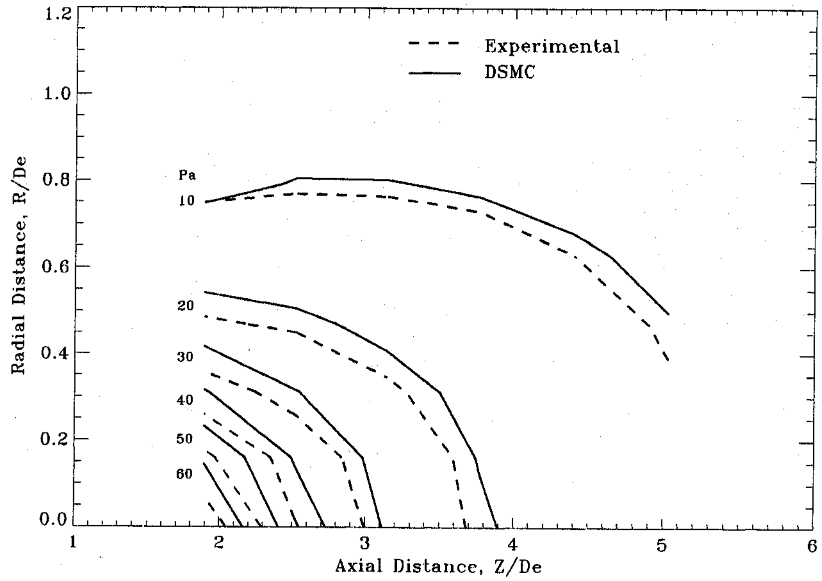

Fig. 2 Comparison of pitot-pressure contours computed with the DSMC method and measured with the 6.4-mm-diam tube.

plume. The 1-mm-diam tube was used in the near field of the plume, from the nozzle exit plane to about 2 nozzle diameters downstream. The 6.4-mm-diam tube was used in the far field of the plume, beyond 2 nozzle diameters of the exit plane. The measurement uncertainty of the pitot tubes depended primarily on magnitude of pressure gradients in the flow, and varied from a maximum of $\pm 9\%$ at the nozzle exit plane for the 1-mm-diam tube to a minimum of $\pm 2\%$ for the 6.4-mm-diam tube at the outer edge of the measurement area.

A probe for measuring flow angle had a 6.4-mm-diam, conically shaped tip with two 1-mm-diam pressure taps located on opposite sides of the cone, each connected to a capacitance manometer. Flow-angle measurements were made by rotating the probe about its tip until the manometer readings were equalized, with the local flow angle taken as the rotation angle referenced to the nozzle axis. The measurement uncertainty of this probe also depended primarily on pressure gradients in the flow, and at the outer region of the measurement area was estimated to be ± 0.7 deg. This probe was used mainly in the far field of the plume, beyond at least 1 nozzle diameter of the exit plane.

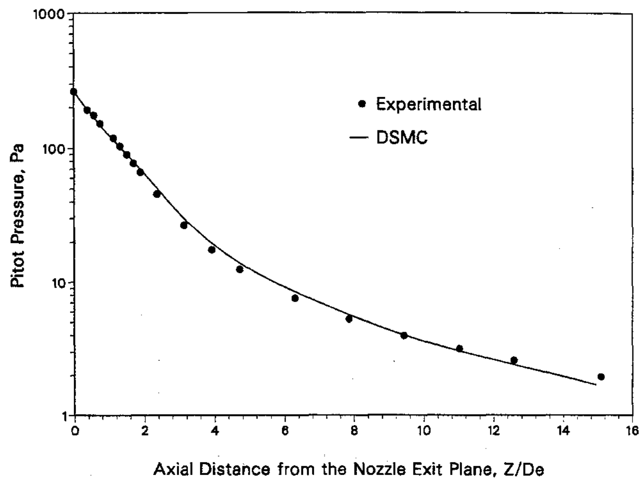

Fig. 3 Comparison of computed (DSMC) and measured pitot-pressure profiles along the plume axis.

DSMC Computation of Plume Flow

In Ref. 1, the DSMC method was applied to an internal nozzle flow, beginning slightly downstream of the nozzle throat and extending into the plume slightly more than a nozzle diameter. In the current application, the computation was begun at the nozzle exit plane using the data generated from this previous DSMC simulation. Expansion of the plume was assumed to occur in a pure vacuum.

A computational grid for the DSMC method was generated in which the cell dimensions were scaled with an assumed profile for the decay in density as a function of distance from the nozzle exit. Densities from the previous solution were used in the near field to about one nozzle diameter, and an inverse-squared relation in the remainder of the field. A computational grid of 88×60 cells covered nearly 16 nozzle diameters axially, and 10 diameters radially. On average, 55 particles per cell were employed in the simulation. Macroscopic flow quantities were obtained by averaging over 2000 time-steps after a transient period of 1000 iterations. The total computational time of the simulation using a vectorized code was 750-CPU s on a Cray Y/MP.

Calculation of Pitot Pressure

To compare the numerical solution with experimental pitot-probe data, pitot pressures were calculated from the DSMC results using the procedure described in Ref. 1. The procedure entails correcting the pressure calculated from the standard Rayleigh pitot-tube equation by employing an experimental relation that accounts for diminution of shock strength from rarefaction effects. The relation is a function of Reynolds number based on probe diameter. Each of the two pitot-tube diameters were experimentally employed in particular regions of the plume to maintain the usable range of probe Reynolds number for applying the relation in calculating comparable pitot pressures from the DSMC results.

Experimental and Computed Results

Measured and computed flow angles are compared in the contour plot of Fig. 1, which shows isograms of flow angle referenced to the nozzle axis. The blank, stepped section in the contours for the experimental data, above a radial distance of 0.7, was an area in the plume where pressure signals from the static taps were too low for measurement. The difference in flow angles between measured and computed results in the region near the nozzle exit plane (to an axial distance of about 2 nozzle diameters), is attributed to large measurement uncertainty of the conical probe from the high-pressure gradients in the flow. Agreement of the results is generally good in the far field of the plume, beyond about 2 nozzle diameters from the exit plane.

Isobars of pitot pressures from computed and experimental results are presented in Fig. 2 for the plume area extending axially from about 1.9–5 nozzle diameters. In this region, the measurements were made with the 6.4-mm-diam pitot tube. The pressures computed from the DSMC method are approximately 10% higher than the measured values.

A comparison is made in Fig. 3 of measured and computed pitot pressures along the plume axis to the maximum extent of the axial-traverse table. The results agree closely over most of the scan. The assumption of a perfect vacuum in the DSMC simulation may account for the slight divergence of measured and computed pressure profiles near the outer edge of the scan.

Concluding Remarks

The experimental tests for this study were designed specifically as a model problem for verification of the DSMC method for a simple, expanding nozzle flow, originally described in Ref. 1. In this article, a larger portion of the plume was computed with the DSMC method and surveyed with aerodynamic probes. The generally good agreement between measured and computed results presented in this study further validates the DSMC method for calculating highly rarefied, expanding flows. Furthermore, the computational time of 750-CPU s demonstrates the relative efficiency of the DSMC method for these calculations.

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