Measurements of a Simulated Rocket Exhaust Plume Near the Prandtl-Meyer Limiting Angle

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Direct measurement of the mass flux level and estimates of the mass velocity have been made in the side flowfield of a small axisymmetric rocket nozzle operated in hard vacuum. A shock tube provided nitrogen and simulated rocket propellant (nitrogen tetroxide and Aerozene 50) sources for the nozzle. Substantial mass flux levels were observed in the neighborhood of the limiting Prandtl-Meyer characteristic. In the inviscid core flow, the measurements compare favorably with method of characteristics predictions of the inviscid flowfield. At large angles a comparison of the data with theoretical predictions that include the expansion of the nozzle boundary-layer gas gives qualitative agreement. In addition, it is shown that reasonable engineering estimates of the boundary-layer portion of the plume can be made using a semi-empirical model.

Nomenclature

A = area, in.^{2}
k = exponent in Roberts' plume model
M = Mach number
P = pressure, psia
q = dynamic pressure, psia
T = temperature, °R; ionization gauge time constant, sec
u = local velocity, *fps*
V = volume; in.^{3}
y = nozzle radius, in.
γ = ratio of specific heats
δ = boundary-layer thickness, in.
δ^* = displacement thickness, in.
θ = polar angle, deg
θ_0 = the limiting turning angle for the streamline at the edge of the boundary layer, deg
ρ = density, slug/ft^3
τ = rise time, sec

Subscripts

℄ = centerline
e = nozzle exit
BL = boundary layer
g = ionization gage
t = stagnation value
$\langle\ \rangle$ = average value

Introduction

NUMERICAL estimates of flow properties that include the expansion of the supersonic portion of the nozzle boundary layer in high altitude plumes indicate that side flowfield flux levels can be several orders of magnitude larger than inviscid predictions. Although the higher flux levels are usually not important to structural loads and heating, this level of gas flow can be significant to problems of contamination of sensors, absorption of radiation, and vehicle stability (torques generated through unanticipated gas flow interaction with large solar paddles, etc.). The existing plume prediction methods [1,2] that are applicable to this problem have not previously been verified experimentally.

Chirivella[3] has recently reported experimental mass flux data in nitrogen and carbon dioxide from a series of five conical nozzles, for angles extending beyond 100° relative to the nozzle centerline. The measured flux levels were normalized to calculated centerline values that were obtained from the Hill and Draper[4] farfield plume model and compared to predicted plume profiles from the same model. Although there appears to be considerable uncertainty in the measured flux levels (in several tests unexplained measurement differences of about a factor of 5 occur at a fixed angle), the results still clearly demonstrate significantly increased flux relative to inviscid theory. The order of magnitude of the differences between experiment and theory indicated here are somewhat misleading because the Hill and Draper modeling underestimates the flux levels near the axis of symmetry and at large angles.[5] The results further indicate that nozzle half angle, expansion ratio, ratio of specific heat, and throat diameter have very little effect on the flow properties in the large angle region of the plume.

In the present investigation, direct measurements of mass flux and estimates of the mean velocity in the hard vacuum plume of a 1/10-scale Lunar Module (LM) Reaction Control (RCS) engine are presented. Measurements are made on the centerline and for angles between 30° and 90° to the centerline. The data are normalized to the measured centerline values and compared to method of characteristics predictions of the inviscid flowfield and to the numerical results of Ref. 1 for a related nozzle/fuel system. In addition, the data from this investigation and selected data from Ref. 3 are compared to predictions from the semiempirical plume modeling technique suggested by Simons.[2]

Experimental Methods

The experiments were performed in the vacuum chamber of the Grumman Research shock tube-driven molecular beam facility (Fig. 1). A shock tube, terminated with a 1/10-scale model of a LM RCS engine, was used to provide combustion chamber gases for the plume studies. The LM engine was chosen as a convenient typical hot gas thruster. The nozzle was isolated from the vacuum chamber by a 0.001-in. mylar diaphragm, and the chamber was evacuated to 10^{-8} atm. Because of the impulse nature of the shock tube flow and the large dimensions of the test chamber, the hard vacuum condition was maintained while the measurements were being made.

Two test gases were employed in the experiments: pure nitrogen and simulated rocket engine combustion products corresponding to the liquid oxidizer and fuel that had been used to power the LM RCS engines (nitrogen tetroxide and

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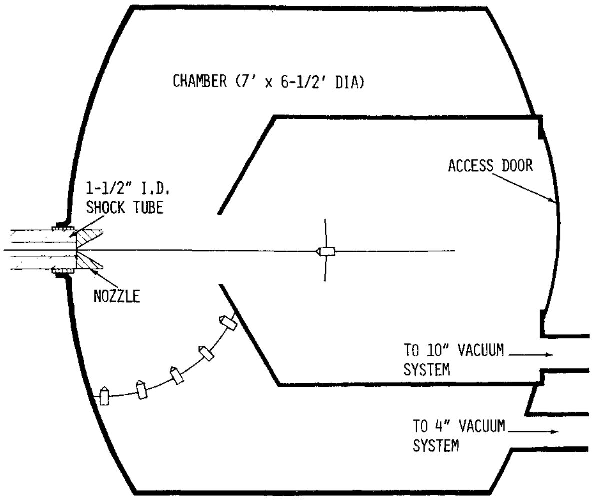

Fig. 1 Schematic diagram of modified molecular beam apparatus.

Aerozene 50). The shock tube was operated in the conventional reflected shock mode for the nitrogen tests and as a reflected detonation tube for the exhaust gas simulations.[6] In the detonation tube mode, the driven section of the shock tube is loaded with a combustible mixture of gases that are ignited by the incident shock wave. The incident shock wave strength is selected in such a way that a constant pressure is maintained by the driver gas behind the detonation wave. the detonation wave travels down the tube and reflects as a normal shock, which further heats and compresses the burned gases. The burned gas properties simulate the combustion products of the actual engine when a proper choice of initial gas mixture is selected.

When the incident wave reflects at the nozzle location, the stagnated gas behind the reflected wave discharges into the vacuum chamber. An array of six ionization gages, in the locations shown in Fig. 1, are used to obtain direct measurements of the local mass flux and time of flight (TOF) velocity measurements. The detector locations are sufficiently far from the nozzle exit to ensure their linear operation across the entire plume for the stagnation conditions used. Because of dynamic range limitations of the detectors and the apparatus dimensions, our measurements are limited to the plume axis and to the side flow between 30 and 90°. The five detectors in the outer chamber (Fig. 1) are mounted on a 25-in. radius circular hoop that is centered in the nozzle exit plane. The hoop lies in a plane of symmetry of the nozzle. The centerline detector is located on a 38.5-in. radius in the same plane. The axisymmetric, bellshaped nozzle has a 10° lip angle, 40:1 area ratio, and a 0.043-in throat radius.

Detectors

The detectors are specially constructed electron bombardment ionization gages. The design[7] is a modified version of the through flow type developed by Hagena and Henkes.[8] A collimated ribbon of electrons is acclerated to 150 ev and allowed to pass perpendicular to the flux of molecules that enters the gage through the conical inlet. Positive ions are formed in proportion to the local instantaneous number density of the neutral molecules. The resulting ions are then collected downstream of the electron sheet by a flat plate collector. The plate collector serves the dual purpose of collecting the ions and stagnating the flowfield.

In the stagnation mode of operation, the local gage density (the ion signal) has a contribution due to the steady-state ambient background molecules and a transient contribution proportional to the local freestream flux. By passing the ion signal through the input resistor of an ac coupled unity gain cathode follower, a transient output voltage is obtained, which at maximum amplitude is a direct measure of the local mass flux. Dynamic calibration of the detector in modulated effusive nitrogen flows established their ionization efficiency at about one part in 10^4. The dynamic range for linear operation of the detector is about 10^5 (the upper limit was established in a nozzle flow). The minimum detectable signal is about 1.6×10^9 N_2 molecules/in.^{3} when the detector is operated at a background pressure of 10^{-8} atm. At this background pressure, the steady-state ion signal generates an rms voltage in a 1-megohm resistor that is the same order of magnitude as the transient signal (electronic bandwidth is about 20 kHz). The upper limit results from the onset of nonlinearities when the electron mean free path becomes the same order of magnitude as the ionizing path length, which is roughly equal to the detector width.

The rise time τ of the transient signal is primarily limited by the gage volume time constant T to about $\tau=2.2T$. It can be shown[9] that if the gage volume is V_g, then $T=4\ V_g/\langle u_g\rangle\ A_g$ where: $\langle u_g\rangle$ =average velocity of the molecules escaping from the gage; it is usually assumed that the gas has accommodated to the wall termperature T_w; and A_g = the total area of all escape ports from the gage. For our detector at room temperature, with $V_g=0.094$ in.^{3} and $A_g=0.28$ in.^{2}, we get $T=80\mu s$ and $\tau=180\mu s$. Since shock tube test times for our experiments are few milliseconds long, the rise time limitations do not affect the mass flux measurements.

Estimates of the local mass velocity are obtained by measuring the time of flight (TOF) to travel the known distance between the nozzle exit and each detector. In effect, for a perfectly instantaneous start at the nozzle exit, the TOF measurements taken at the half height of the leading edge of the flux signal give a measure of the median molecular velocity. For the high exit Mach number nozzle used in these experiments ($M_e\approx4.0$), the distribution of velocities about the mean is very sharp, and the median flight time should be within a few percent of the mean flight time.

In practice the measured velocities underestimate the mean velocity across the entire plume because the flowfield is not established instantaneously (nozzle starting time is approximately $25\mu s$), and the pulse shape is not faithfully reproduced (rise time limited). The combination of these two sources of error could result in at most a 30% underestimate of the mean velocity for the N_2O_4/A-50 tests and a 15% underestimate for the N_2 tests. The error estimates are quite conservative as they have been made assuming a step function density pulse at the detector inlet (monoenergetic flow) and a mean velocity corresponding to complete conversion of the stagnation enthalpy ($u=u_{max}$). Measurements on the plume axis, where the fastest rise times are observed, are well within this error bound. For the N_2O_4/A-50 tests $u_{max}=11{,}000$ fps and the measured velocity is about 8000 fps; while for the N_2 tests, $u_{max}=5500$ fps and the measured velocity is about 5200 fps. Note that if vibrational freezing occurred during the N_2O_4/A-50 tests, the limiting velocity would be reduced to 8500 fps and the measured velocity in that case is only about 6% low.

Results

In Fig. 2, the measured mass flux and velocity profiles for the nitrogen and N_2O_4/A-50 plumes are compared to an inviscid calculation by the method of characteristics.[10] The data at each angular location have been normalized to centerline values. The nitrogen data shown are representative results for stagnation pressures in the range $200\leq P_t\leq650$ psia, while the N_2O_4/A-50 data for $P_t=165$ psia. Each data point shown is the average of at least six test runs (corresponding to the use of six different detectors at every location shown in Fig. 1); the average deviation is less than 10% at all locations. To normalize the mass flux centerline data were first corrected to the same radius (i.e., distance from the throat) as the other detectors using the inverse-square scaling law for the density.

The measured data agree quite well with inviscid predictions in the core flow, but there are very significant effects of

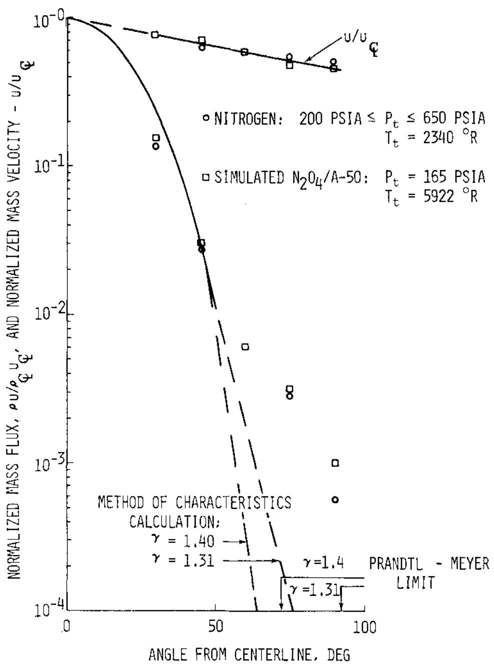

Fig. 2 Normalized mass flux and velocity measurements in the plume of a 1/10-scale Lunar Module RCS engine.

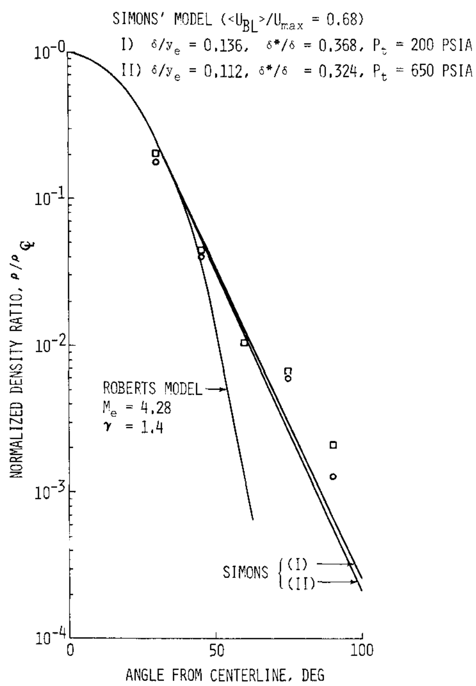

Fig. 4 Comparison of measured density ratio with predictions from Simons' model.

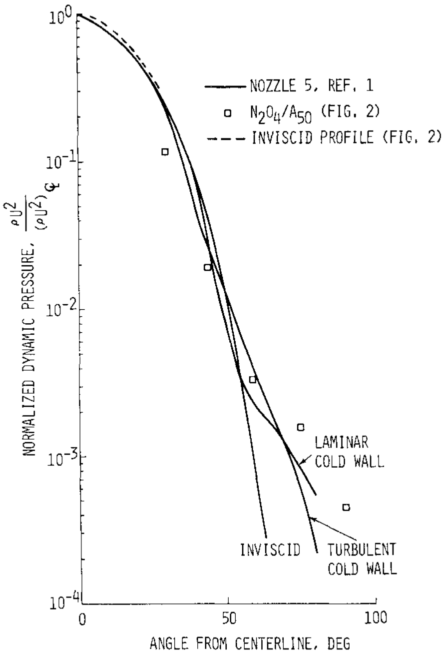

Fig. 3 Comparison of measured dynamic pressure profile with Boynton's predictions.

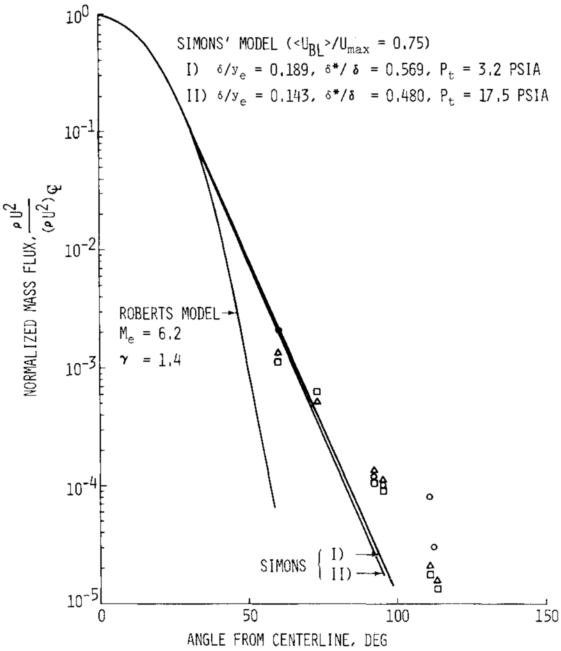

Fig. 5 Comparison of Chirivella's measured flux ratios with predicted density ratio from Simons' model.

the boundary-layer flow in the peripheral region. At $\theta = 90°$ the measured flux is only three orders of magnitude lower than the centerline level. This is in the proximity of the Prandtl-Meyer limiting angle, where inviscid theory predicts near zero flux levels. The increased flux level at large angles is accompanied by a flux deficit near $\theta = 30°$. Furthermore, there appears to be very little effect on the large-angle data that is attributable to differences in molecular weight/or specific heat ratio of the test gases.

For both test gases (i.e., N_2 and exhaust products) the TOF measurements indicate an exponential decrease in velocity with increasing angle from the centerline as can be seen in the top curve of Fig. 2. At 90° the velocity is approximately 50% of the centerline value. It is interesting to note that Boynton's numerical calculations also indicate an exponential decrease of velocity in the large-angle region of the plume. His predictions of normalized density and dynamic pressure profiles for Nozzle 3 indicate a constant core velocity between the nozzle centerline and $\theta = 45°$ followed by an exponentially decreasing velocity. The absence of a uniform core in the data may be peculiar to the experimental nozzle, which is known[10] to have a nonuniform exit Mach number profile across the nozzle owing to the presence of weak shocks that are generated by inner nozzle reflections.

In Fig. 3, Boynton's results for a 25° conical nozzle employing the monopropellant N_2H_4 (Nozzle 5) are reproduced and compared to the experimental data of Fig. 2. Here, values of the normalized dynamic pressure ratio $q/q_{℄} =$

$(\rho u/\rho_{\mathrm{\not{c}}} u_{\mathrm{\not{c}}})x(u/u_{\mathrm{\not{c}}})$ calculated from the measured N_2O_4/A-50 data of Fig. 2 are plotted as a function of angle relative to the nozzle centerline. The theoretical results are in qualitative agreement with the measurements in the large-angle region. Boynton's boundary-layer plume results also show the general structure of the measured profile. A flux deficit is present in the neighborhood of $\theta = 50°$ and $\theta = 30°$ for the laminar and turbulent cases, respectively. A qualitative comparison between theory and experiment is possible here because there are no major differences between the inviscid profiles of the two nozzles (beyond $\theta \approx 30°$ they are indistinguishable). and the theoretical operating conditions produce a nozzle Reynolds number that is the same order of magnitude as that employed in this work (Fig. 2).

Based on Boynton's numerical results, Simons[2] has generated a boundary-layer plume model that permits plume properties to be simply expressed in terms of the boundary-layer thickness and nozzle exit conditions. In this model an exponential density profile is matched to an inviscid profile at an angle θ_0, where θ_0 is the limiting turning angle for the streamline at the edge of the boundary layer. The exponential decay factor is determined as a function of θ_0 and the boundary-layer properties from mass conservation. Note that turbulent and laminar boundary layers are distinguishable only through δ, the boundary-layer thickness, in this model. In Fig. 4 density profiles derived from the data shown in Fig. 2 are compared to theoretical predictions from Simons' model. Two theoretical curves are shown corresponding to the extremes of operating stagnation pressure used in the N_2 tests. As can be seen the agreement between theory and experiment is reasonable. Furthermore, the small effect of Reynolds number displayed by the theoretical predictions is consistent with the fact that no measurable difference in mass flux could be observed in the experiments.

In the theoretical computations, Roberts'[11] model ($\rho(\theta) \propto \cos^k\theta$) was selected for the inviscid plume as this model gave the best fit to the characteristics solution of the several such models that were tried. The boundary-layer thicknesses, δ^* and δ, were obtained from empirical relationships developed by Burke[12] for turbulent boundary layers, and the average velocity in the boundary layer $\langle u_{BL} \rangle$ was estimated from velocity measurements in the plume ($\langle u_{BL} \rangle / u_{max} = 0.68$).

As a further test of the theory, Chirivella's[3] measurements of normalized mass flux in a conical nozzle exhaust (Nozzle 5) are shown in Fig. 5 along with predictions from Simons' model. Since measured velocity profiles are unavailable, a direct comparison with the predicted density profiles is not possible here; however, the engineering utility of Simons' method is clearly demonstrated.

Conclusions

Measurements of the angular distributions of mass flux, and mass velocity in the exhaust of a simulated high altitude rocket have been reported. The results of these experiments are in good qualitative agreement with Boynton's[1] numerical calculations that include the expansion of the supersonic portion of the nozzle boundary layer. The measurements demonstrate several features of the plume that were not readily apparent in the theory: 1) the increased flux levels in the neighborhood of and beyond the limiting Prandtl-Meyer angle are accompanied by an exponential decrease in velocity and 2) the large angle flux levels are quite insensitive to gas properties and Reynolds number within the threefold *Re* range tested. Furthermore, it was shown that it is possible to make reasonable engineering estimates of boundary-layer plume properties from nozzles operating with up to about 20% boundary-layer thickness by using Simons'[2] model.

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