Experimental Evaluation of Resistojet Thruster Plume Shields

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The exhaust plume characteristics of an engineering model resistojet have been evaluated using rotary pitot and quartz crystal microbalance probes. The resistojet operated on CO_2 propellant at a mass flow rate of 0.29 g/s in both heated and unheated flows. Measurements of local flow angles in the near field of a conical plume shield indicated that the shield was not wholly effective in confining the flow to the region downstream of its exit plane. However, the absolute levels of the measured flux into the backflow region were very low, on the order of 7×10^{-7} g/cm²-s or less. The use of a circular disk at the exit plane of the existing conical shield showed some benefit in decreasing the amount of backflow by a factor of 2. Last, a detached shield placed upstream of the resistojet exit plane demonstrated a small degree of local shielding for the region directly behind it.

Nomenclature

A	= nozzle area, m²
D^*	= nozzle throat diameter, m
D_e	= nozzle exit diameter, m
D_p	= pitot probe orifice diameter, m
D_s	= conical shield exit diameter, m
K	= constant for Eq. (2)
M	= Mach number
$\dot{M}$	= mass flux, g/cm²-s
$\dot{m}$	= mass flow rate, g/s
P	= gas pressure, N/m²
P'_0	= measured pitot pressure, N/m²
R	= radius from plume centerline, m
r	= radial distance from thruster exit plane to center of quartz crystal microbalance crystal, m
T	= gas temperature, K
U	= gas velocity, m/s
z	= axial distance from conical shield exit plane, m
γ	= specific heat ratio
θ	= angle from plume centerline, deg
μ	= viscosity, N-s/m²
ρ	= gas density, number/m³
ϕ	= nozzle half-angle, deg
Ω	= solid angle, sr

Subscripts and Superscripts

e	= exit plane conditions
i	= inlet conditions
max	= maximum
0	= stagnation conditions
*	= sonic conditions
∞	= freestream static
2	= conditions downstream of normal shock

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Introduction

THE multipropellant resistojet thruster has been baselined for auxiliary propulsion applications onboard the Space Station Freedom (Level B Space Station Control Board Directive). The thruster offers low thrust propulsion for drag makeup and also the capability for propulsive, or nonpropulsive venting of waste gases. A NASA-sponsored study[1] has indicated that use of the resistojet in conjunction with a hydrogen/oxygen primary propulsion system is advantageous in terms of both development and operational cost. A 48% decrease in total propulsion system life cycle cost over a 10-yr period was predicted over a stand-alone system. However, as with the high thrust propulsion system and other sources of effluents, the exhaust flowfield of the resistojet must be well defined prior to integration because of the potential impacts that the plume may have on station science and technology activities. Induced environmental contamination during quiescent periods and mass deposition on sensitive surfaces are considerations of primary concern. Thermal loading and torques resulting from plume impingement may also be matters of concern, depending on the space station architecture.

A number of diagnostic techniques have been developed for the measurement of nozzle plume properties.[2,3] Experimental studies of pure gas expansions into a hard vacuum have investigated the effects of nozzle area ratio and lip geometry, facility pressure, condensation, and cryopumping in the backflow region. Investigations of the resistojet plume[4,5] have shown that, with CO_2 propellant at 298 K, the flow expanded beyond a calculated limiting turning angle using continuum methods. The amount, however, represented only a very small fraction of the total thruster throughput.

An experimental investigation has been conducted to measure the level of backflux from an engineering model resistojet developed for space station application and also to evaluate the effectiveness of plume shields in preventing or minimizing the backflux. Three specific shield types were evaluated: 1) a large, conical plume shield integrated in the design of the engineering model thruster[6]; 2) circular disks positioned at the exit plane of the conical shield; and 3) a flat plate placed upstream of the thruster exit.

This paper presents an initial evaluation of the experimental data obtained from the resistojet plume. Details of the measurement techniques and experimental hardware are provided along with a brief description of the test facility. The near-field plume character of the resistojet is described in terms of dynamic pressure profiles and local flow angle variation for the different shield configurations. Other data to be presented include estimates of Mach number variation along plume centerline, radial dynamic pressure profiles for heated and unheated flow, and mass flux variation in the plume as a function of radial and axial distance. Absolute values of measured mass flux are compared with similar experimental measurements obtained in other investigations.

Apparatus

Engineering Model Resistojet

The resistojet thruster used in this investigation was an engineering model, designed and fabricated for space station application.[6] Propellants for this thruster will be inert gases, water vapor, carbon dioxide, carbon air, methane, and hydrogen present in the Environment Control and Life Support System, Materials Technology Laboratory, and Attached Payloads. Because the propellant supply would be readily available, performance was not a major design criterion. Instead, the design goals were a 10,000-hr lifetime and a multipropellant capacity. Figure 1a displays a cutaway schematic of the resistojet. The propellant passes through a multichannel heat exchanger, which is conductively and radiatively heated from a double helix sheathed heater. Several layers of radiation shields surround the heater assembly.

The nozzle is a 25-deg half-angle cone with a throat diameter of 0.102 cm (0.040 in.), followed by a trumpet flare. Its exit diameter is 5.07 cm (1.998 in.), giving an overall nozzle area ratio of 2500. A large 45-deg cone is attached at the end of the trumpet flare as a plume shield. The small holes, which are visible (see Fig. 1) between the flare and the shield, are fail-operational vents, which ensure that in the event of propellant leakage all gas would vent in the thrust direction. Complete details of the design, fabrication, and performance of the engineering model resistojet may be found in Refs. 6 and 7.

Plume Shield Configurations

The various shield configurations used in this investigation are shown in Figs. 1b and 1c. As noted above, a conical plume shield was integrated into the engineering model design. The large cone is a half-angle of 45-deg and an exit diameter of 9.65 cm. It was not expedient to remove this shield to determine its relative effectiveness over the nozzle alone. A second shield configuration made of thin, concentric stainless steel disks positioned in the exit plane of the conical shield is shown in Fig. 1b. Two circular disks were tested, having outer diameters of 17.8 and 22.9 cm, respectively. Last, a detached shield, placed at a distance 10.8 cm upstream of the conical shield exit plane, was tested in order to measure the degree of local shielding which could be obtained. The detached shield was a thin stainless steel plate which extended outward 33.7 cm from the centerline as shown in Fig. 1c.

Instrumentation

There are a number of diagnostic techniques available for the local, quantitative measurement of flowfield properties. However, the backflux region of the resistojet plume, because of its low absolute number density and steep property gradients, precludes the immediate adaptation of a variety of nonintrusive optical techniques which are limited to number densities above $10^{11}/cm^3$. Consequently, two intrusive probe techniques, a rotary pitot probe and a rotary quartz crystal microbalance (QCM), were used to define the resistojet plume.

It has been shown[2] for hypersonic flows that a rotary pitot probe is a simple effective technique for the measurement of dynamic pressure (ρU^2) and local flow angle. The rotary probe described in Ref. 2 consists simply of an open-ended, flat-faced tube, which is aligned with the open end facing toward the gas flow, with the other end of the tube attached to an absolute pressure transducer. Pitot pressure measurements are an excellent means for obtaining the local velocity vector as they are extremely sensitive to local flow angle variation. The pitot probes used in this investigation had diameters of 0.152 cm (0.06 in.) and 0.635 cm (0.25 in.). The absolute pressure transducers ranged in pressure response from 1×10^{-2} to 4×10^5 N/m^2 (1×10^{-4} to 3×10^3 Torr).

The QCM is an established technique for contamination monitoring and the mapping of exhaust flowfields.[2,3,8,9] Basically, the QCM consists of a matched pair of crystals, which are cryogenically cooled to temperatures sufficient to collect mass on one of the crystals (sensor crystal), whereas the other crystal serves as a reference. The QCM relates a change in beat frequency between the two crystals to the amount of mass loading. Previous calibration[2] of the QCM in a flow of known mass flux indicated a measurement uncertainty of 15%. Based on this information, it has been concluded that this is a reasonable measure of the uncertainty of the measured mass flux for the present study.

Test Facility and Experimental Setup

The plume experiments were conducted in a vacuum chamber having an inner diameter of approximately 1.1 m and a length of 4.3 m. The chamber is equipped with a mechanical

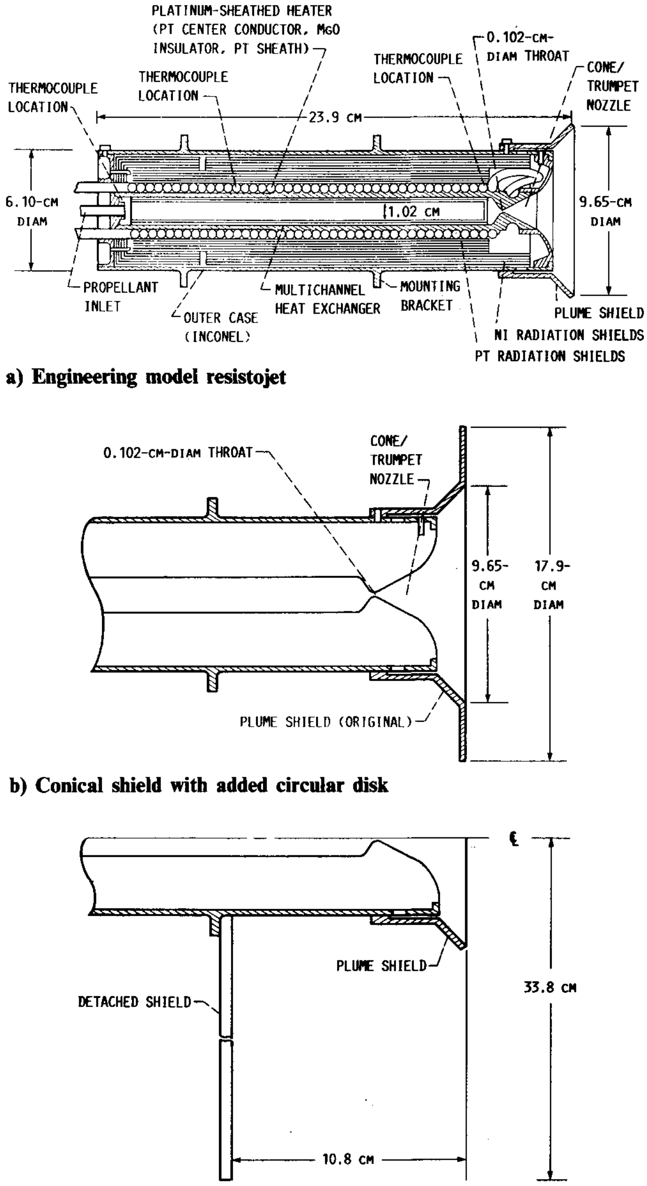


Fig. 1 Engineering model resistojet and plume shield configurations.

roughing pump and two oil diffusion pumps. However, the majority of the pumping is achieved through the use of cryogenically cooled (77 K) baffles that line the inner surface. Throughout the experiments, the facility maintained a background pressure on the order of 1×10^{-3} to 5×10^{-3} N/m^2 (8×10^{-6} to 4×10^{-5} Torr).

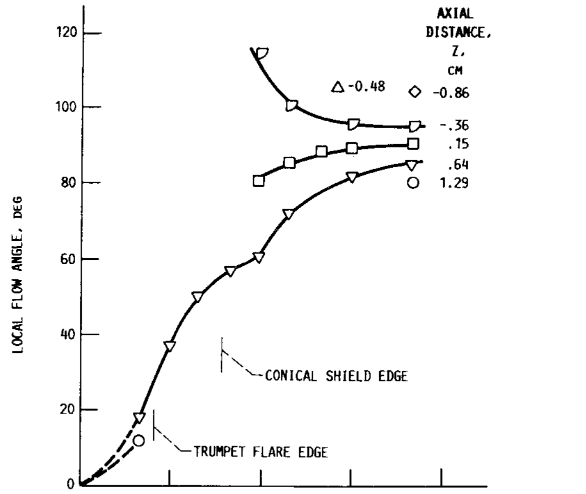
The engineering model resistojet was mounted on a dual axis traversing mechanism and was aligned with the chamber centerline. The center of the plume shield exit plane, as opposed to the true nozzle exit plane, was used as the zero reference for all probe measurements. Both the QCM and the pitot probe were mounted on motor-driven, rotary mechanisms. The movement of the thruster and probes could be controlled manually or with a computer. Changes in the position of the probes with respect to the nozzle centerline were accomplished by positioning the probes at a fixed location and moving the resistojet. The angular orientation of the probes was then adjusted using the rotary devices.

Procedure

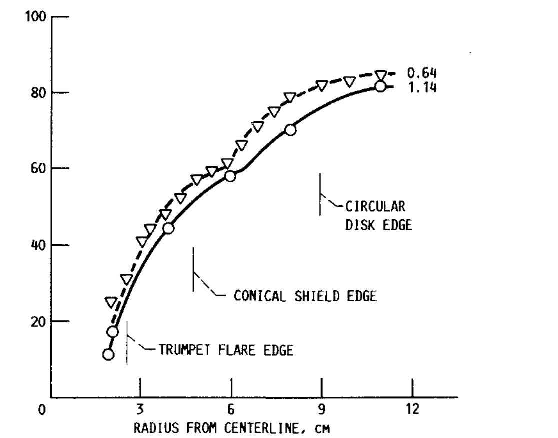
The pitot probe and QCM were accurately positioned both axially and radially with respect to the shield exit plane prior to the facility pump down. It was not possible to detect any movement of the probe or nozzle as a result of chamber evacuation. However, as the chamber was cooled cryogenically and the thruster heated, axial movement of the lip of the conical plume shield was observed. An accurate measurement of this growth was determined by tracking the nozzle axially until the lip was once again aligned with the probe. This correction was made for all test conditions. Although it was not possible to measure the radial growth of the nozzle, it was determined from complete radial surveys in the exit plane that the thruster axis did not move radially as the thruster components were heated. Depending upon the test requirements, it was found that between 2 and 3 hr were required to bring the chamber and resistojet to the desired operating conditions, i.e., thruster temperature, gas temperature, and cryoliner temperature to a steady-state condition. Sufficient temperature and pressure instrumentation was available to monitor the performance of the complete chamber/thruster configuration.

In keeping with earlier performance evaluations of the resistojet using CO_2 as a propellant,[7] a mass flow rate of 0.29 g/s was selected for both the unheated and heated flow tests. For the heated flow tests, the heater current was set to 23 A giving a steady-state heater power of 405 W. Measurements of pressure were made on the centerline as a function of axial distance for both unheated and heated flow. Pitot pressure measurements as a function of radial distance from the thruster centerline were then made at various distances downstream of the exit plane. Complete rotary surveys of pitot pressure were also made at a number of positions in order to define the angle of the local flow velocity vector.

Accurate measurements of local mass flux require that the QCM be aligned with the local velocity vector. Because of the time-consuming nature of QCM measurements, it was originally intended to make these measurements with the QCM aligned with the local velocity vector, where the local velocity vector had been defined from previous rotary pitot measurements. However, as will be described in a later section, the pitot probes could not be used to measure flow angle in the region upstream of the circular disk configurations. Consequently, complete rotary surveys with the QCM had to be made at each measurement location to define local flow angle. This time consuming process limited the amount of information which could be obtained for a given test condition. In order to define the gross variation of mass flux in this region, it was decided to make a number of the axial mass flux measurements by setting the QCM at a fixed radial distance from the plume centerline (23.8 cm) and at a fixed angular orientation to the thrust axis (146 deg). Last, the Bayard-Alpert ionization gauge was also used to measure axial pressure variation at large radial distances.



a) Resistojet with 9.6-cm-diam conical shield only



b) Resistojet with additional 17.8-cm-diam shield (dashed line is conical shield only data; flow angle indeterminate with pitot probe at −0.36 cm upstream with circular disk in place)

Fig. 2 Local flow angle variation with axial and radial distance (heated flow).

Results and Discussion

This section presents the results of the experimental investigation of the plume resulting from the operation of the resistojet in hard vacuum. The near field of the plume is described for unheated and heated flow in terms of dynamic pressure and local flow angle, along with estimates of the centerline Mach number variation. Mass flux data taken with the rotary QCM is presented as a function of angle off plume centerline for the resistojet, with and without a circular disk shield. Absolute values of measured mass flux are also compared with similar experimental measurements of related investigations.

Pitot Probe Surveys

It is beyond the scope of the present paper to include examples of all the pitot measurements made in support of the present study. Some general comments with regard to the extensive pitot pressure measurements are appropriate in that they illustrate sensitivity of such measurements to environmental and hardware changes. Of importance in a test program of this type is the repeatability of the test conditions. Throughout the course of the present study the variation of pitot pressure on the thruster centerline as a function of axial distance from the thruster was monitored on a regular basis. A review of these measurements has shown that, provided

Table 1 Comparison of backflux data

	Engineering model resistojet, present	Conical nozzle expansion[a]	Simulated hydrazine thruster[b]	Bipropellant engine[c]
P_0, N/m^2	2.7×10^5	1.5×10^5	2.7×10^5	7×10^6
$\dot{m}$, g/s	0.295	0.68	0.34	-5 to 7 g/s, 100 ms pulse
Nozzle type	Cone/trumpet +45-deg shield	Conical thick lip	Conical	Contoured
Nozzle area	2500[d]	360	60	50 to 100
Collected gas species	CO_2	CO_2	N_2	Condensible exhaust products of N_2O_4/MMH
Angle off-centerline, deg		Absolute[e]	$(d\dot{M}/d\Omega)_\theta$	g/s-sr
80	1×10^{-4}	4×10^{-3}	2.9×10^{-3}	1×10^{-2}
110	9×10^{-5}	3×10^{-4}	1.8×10^{-3} 5.9×10^{-3}	1×10^{-3}
140	—	—	8.8×10^{-4}	1×10^{-4}
Angle off-centerline, deg	Ratio of $\dot{M}/\dot{m}$			
80	1×10^{-6}	8×10^{-6}		
110	3×10^{-7}	6×10^{-7}		

[a]Ref. 3. [b]Ref. 9, Fig. 23a. [c]Ref. 11. [d]Area ratio considering conical shield exit plane. [e]Where $(d\dot{M}/d\Omega)_\theta = \dot{M}r^2 \cos\phi$, g/s-sr.

mass flow and power to the thruster were carefully controlled, these pitot pressure measurements were repeatable to better than $\pm 2\%$.

Measurements of pitot pressure as a function of distance from the thruster center have been obtained at a number of locations downstream of the thruster exit plane. For chamber pressures of 1×10^{-3} to 5×10^{-3} N/m^2 (7.5×10^{-6} to 4×10^{-5} Torr) there are no indications of shock waves in the plume. At a chamber pressure of 3 N/m^2 (2×10^{-2} Torr), there is a pronounced off-centerline spike in the pressure profiles, which is indicative of an outwardly expanding shock wave that has been generated upstream of the thruster exit plane. The radial pressure profile close to the thruster exit plane is characterized by 1) a small inviscid core flow region (approximately 2 cm as compared to the conical shield diameter of 9.65 cm) and a correspondingly thick boundary layer, i.e., approximately 3.8 cm; 2) off-center humps in the profiles, which are indicative of a transition from the inviscid core condition to thick viscous layer; and 3) an asymmetry in the radial profile, which can be attributed to an internal asymmetry within the thruster that resulted from a small misalignment of the center shroud and nozzle during assembly.[7] Further downstream of the exit plane, the inviscid core flow dissipates, and the profiles become more symmetrical. The form of the downstream profiles is such that there are no indications of regions of separated flow within the exhaust plume.

Pitot probe flow angle measurements obtained for the resistojet, with and without a circular disk, as a function of radial and axial distance are presented in Fig. 2. The locations of the edges of the trumpet flare, the conical plume shield, and the circular disk are identified in the figure. The flow does not remain parallel to the 45-deg conical shield as the local flow angle at the edge of the shield is approximately 20 deg greater than that of the shield. The 17.8-cm disk placed at the edge of the existing shield did not have a marked effect on local flow angle variation except that it confined the boundary-layer flow along its surface until the flow reached its lip. Also, in the case of the added circular disk, it was not possible to obtain accurate measurements of flow angle for the measurement locations upstream of the exit plane (see Fig. 2b) even at radial distances exceeding the edge of the disks. This qualitatively suggests a reduction in backflow, but, as will be shown later, there is still evidence of flow in the region upstream of the concentric disks. It should be noted that the absence of pitot pressure profile data in this region is simply a limitation of the particular probe/transducer arrangement used. The minimum detectable pitot pressure which could be measured was approximately 1×10^{-2} N/m^2. However, in practical application, maximum pitot pressures of at least 4×10^{-2} N/m^2 were needed to determine the local flow angle with a reasonable degree of certainty. Finally, the pronounced kinks in the flow angle profiles deserve comment. It is unlikely that they denote the transition from inviscid core to boundary-layer flow as they occur too far off-center. Most probably the kinks are a result of the step variation from the edge of the trumpet flare (at an angle approaching 90 deg) and the conical shield (half-angle of 45 deg), but there are insufficient data to document this possibility.

Ionization Gauge Measurements

A Bayard-Alpert ionization gauge positioned normal to the thruster axis was used to survey the backflow region of the engineering model resistojet. As the relative gauge position crosses through the exit plane, there is a rapid decrease in the measured pressure. The ion gauge measurements support the previous discussion in that there is a flow originating in the region of the nozzle lip region at flow angles well beyond that of the conical shield (45 deg). Using 1×10^{-3} N/m^2 as a point of reference for the backflux region gives a background molecular number density of 2×10^{11}/cm^3.

Mass Flux Measurements

Complete rotary surveys with the QCM were made at a number of locations in the backflow region. Because of the sensitivity of the device, it was often not possible to complete a rotary survey before the sensor crystal was overloaded with condensed CO_2. The surface had to be cleaned by warming the QCM and then recooling. Rotary QCM measurements of mass flux as a function of angle to thrust axis at the same location for two separate surveys show that the repeatability of the data falls within the estimated uncertainty of the measurement technique. Rotary scans obtained with the QCM as a function of axial distance at a fixed radius from the plume centerline are shown in Fig. 3. The data are presented in units of g/s using the sensor crystal area of 0.316 cm^2. For

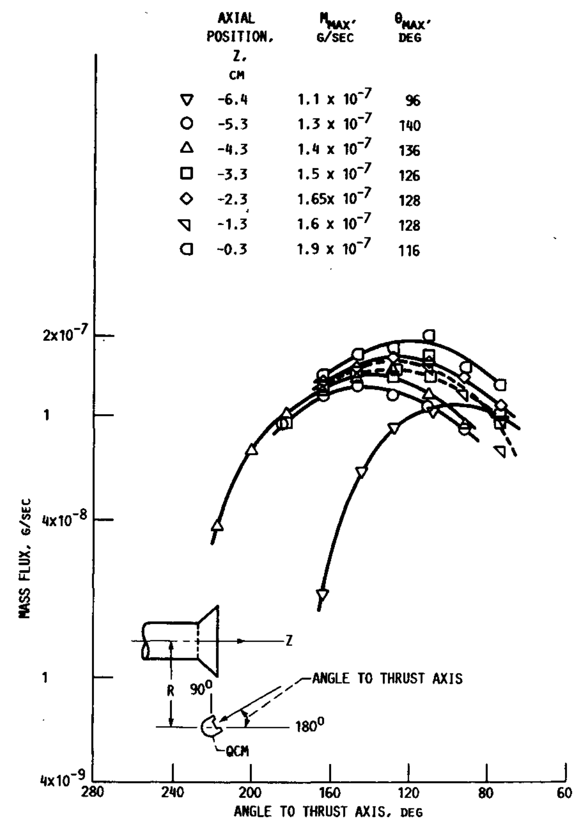


Fig. 3 Variation of mass flux with angle to thrust axis for various positions ($R = 23.9$ cm); heated flow; conical shield; and 17.8-cm-diam disk.

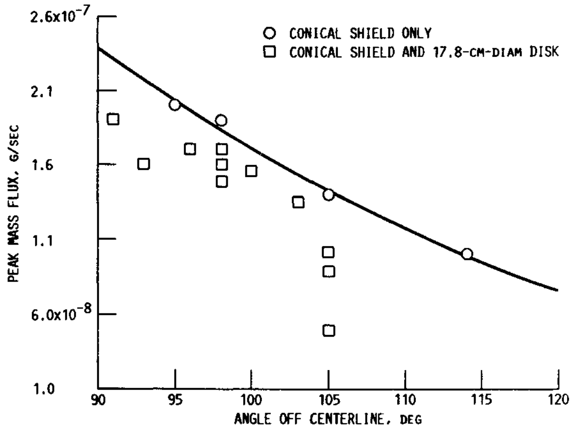


Fig. 4 Mass flux as a function of angle off centerline (radial distance $R = 23.9$ cm).

the most part, the data approximate a cosine distribution near the peak, which has been taken to be suggestive of a directed, free molecular flow into the backflux region. The angle at which the maximum mass flux occurs is assumed to be the local flow angle. A review of these data indicates that the flow does not originate from the lip of the conical shield in that the detrmined flow angle is larger than the expansion angle from the lip of the plume shield. A possible explanation for the large angle data is that the large angle flow around the shield is the result of molecular self-scattering within the plume.[10] The average background level of mass flux to the QCM in the region upstream of the thruster exit plane was on the order of $2\text{–}4 \times 10^{-8}$ g/s. Contributions to this background level of mass flux included scattering off of the hot surfaces of the thruster and mounting configuration, particularly in the data obtained without a circular disk. Although the presence of nonpumping surfaces is more representative of an actual spaceflight configuration, it made interpretation of some of the QCM data difficult. For example, the local flow angle at an axial position of 6.4 cm (see Fig. 3) is not consistent with those obtained for the other axial positions, and it is assumed that this measurement has been affected by scattering from nonpumping surfaces in the backflow region. Effects of this type have been observed in conical nozzle flow expansions into a vacuum.

In the discussion of mass flux/unit angle, it has been assumed, as has been the case in discussions of similar data,[9,11] that the nature of the plume flow is such that it can be treated as a source flow. From a consideration of the data presented in Fig. 3, it is apparent that the flow in the backflow region is not source-like and does not originate at the shield lip. This is evidenced by the fact that the angle of the local velocity vector at a point in the flow is greater than the geometric angle at that point. Similar results have been obtained for expansion from conical nozzles into a hard vacuum.[2,3] The possibility exists that the present and earlier[2,3] measurements have been obtained too close to the nozzle to be representative of far-field data. However, although these measurements show that in the region where they were obtained the flow is not source-like, it cannot be assumed that other measurements of the type[9,11] were obtained in a flow regime where the flow was source-like. There is no way of determining that the QCMs in those tests[9,11] were aligned with the local velocity vector and it is, therefore, impossible to determine the relationship between the geometric angle of the detector and the local velocity vector. The determination of the boundary between near-field and far-field characteristics was beyond the scope of the present investigation. Further testing with a smaller thruster in a larger test chamber would be required to resolve this question. In general, mass flux tests in which there was evidence of scattering phenomena occurring were not used in the following data analysis. The peak mass flux data from the rotary scans are plotted in Fig. 4 as a function of angle off the centerline for the resistojet, with and without the various shield configurations. It appears that the effect of increased lip thickness is to reduce the mass flux into the backflow region by a factor of 2. Figure 5 presents a similar result with a plot of mass flux data as a function of axial distance at a constant radial location. Measured mass flux values of the engineering model resistojet are compared with the backflux from monopropellant and bipropellant thrusters in Table 1. In order to account for differences in QCM mounting arrangements, the data are presented in terms of mass flux per unit solid angle. It is of interest to observe that the absolute levels of mass flux appear to be at

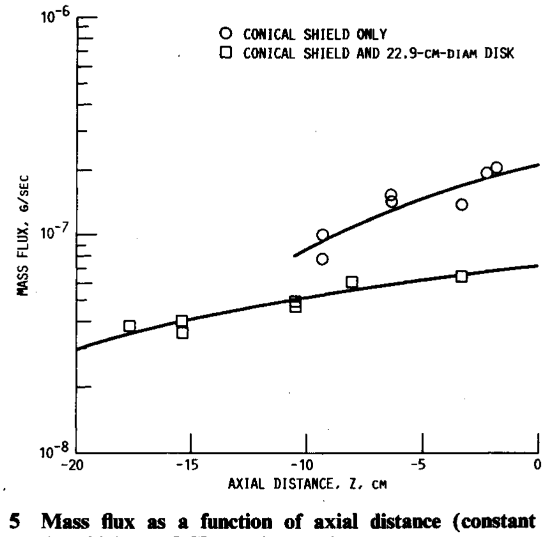
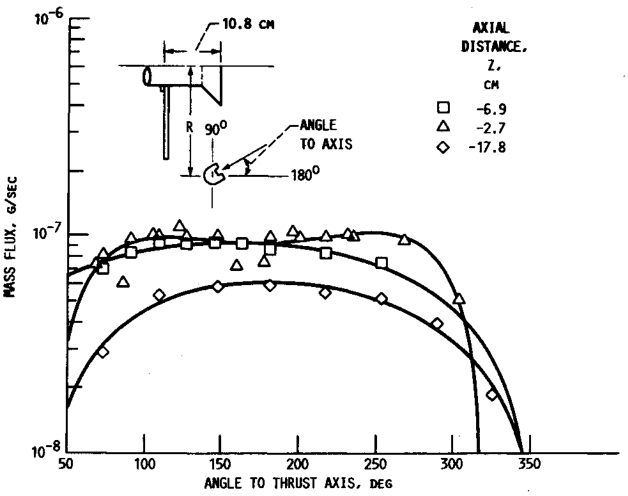
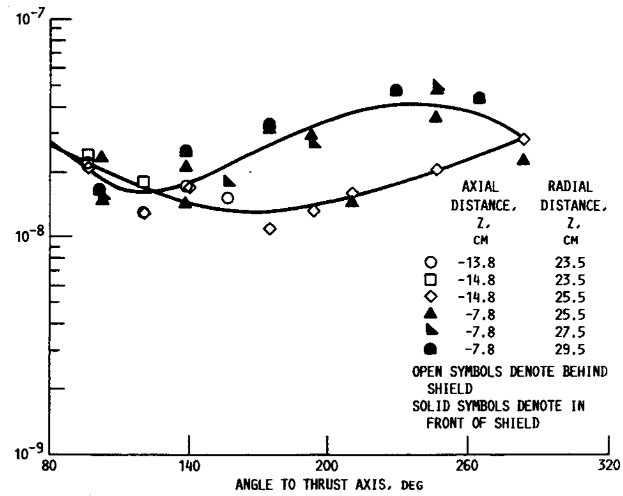


Fig. 5 Mass flux as a function of axial distance (constant radial distance $R = 23.9$ cm; QCM angle = 146 deg).



a) Radial distance $R = 39$ cm



b) Various radial distances

Fig. 6 Mass flux as a function of rotary angle; detached shield located at axial distance $Z = -10.8$ cm.

least one to two orders of magnitude lower than the higher thrust propulsion systems.[9,11] The relative amount of backflow from the resistojet nozzle configuration is also compared to that of a standard conical nozzle by relating the level of measured mass flux at discrete angles off the centerline to the thruster total mass flow rate. The ratio of local mass flux to the total mass flow rate for the resistojet is lower than that of the conical nozzle[2] by factors of 2–8, which suggests that the existing conical shield is of value in reducing the mass flux into the backflow region. As a conservative estimate, less than 0.2% of the total resistojet mass flow expands into the backflux hemisphere.

Detached Shield Configuration

Only a limited amount of data was obtained for the detached shield arrangement shown in Fig. 1c. Mass flux as a function of angle to the thrust axis for discrete locations in front of and behind the detached shield are shown in Fig. 6. In Fig. 6a the QCM is located just beyond the edge of the shield at $R = 39$ cm. Although the mass flux behind the shield is slightly lower than in front, it appears that the measured mass flux is a result of random scatter rather than a directed flow as there is no apparent peak in the mass flux levels. Figure 6b presents a similar result for various radial distances within the dimensions of the detached shield. There is some indication that the presence of a nonpumping surface in the backflow region contributes to a recirculatory flowfield just ahead of it. The effects of nonpumping surfaces in the backflux region have been documented previously.[2] The degree of local shielding offered by the detached shield appears minimal.

Concluding Remarks

Surveys in the exhaust of an engineering model resistojet developed for space station application have been made using a rotary pitot probe and rotary quartz crystal microbalance. The resistojet operated on CO_2 propellant at a mass flow rate of 0.29 g/s in both unheated and heated flow (405 W). It is apparent from the measurements of local flow angle in the near field of the nozzle exit plane that an existing conical plume shield does not wholly prevent the viscous boundary-layer flow from expanding into the backflow region and that the expansion in this region is not source-like in nature. However, measurements with a rotary QCM indicated that the absolute levels of backflux were very low, on the order of 7×10^{-7} g/cm²-s or less. When related to the total thruster mass flow rate, the backflux is lower than that observed in a previous investigation of CO_2 expansion from a conical nozzle. It was not possible to evaluate the level of backflux from the resistojet without the existing conical shield. Also, it is noteworthy that the absolute levels of backflux from the engineering model resistojet are lower than that of monopropellant and bipropellant thrusters. A circular disk placed at the edge of the existing shield further reduced the backflow expanding beyond 90 deg by a factor of 2. Last, a detached shield located upstream of the thruster exit demonstrated a small degree of local shielding. However, the presence of a nonpumping surface in the backflow region appears to create a recirculatory flowfield just ahead of the surface. Further work is needed to better quantify the merits of local shielding.

The exhaust flowfield of the engineering model resistojet has not been fully characterized. A detailed experimental evaluation of the interior nozzle flowfield is needed to accurately define the gasdynamic processes occurring for this particular nozzle configuration. It is suggested by the authors that the unusual nozzle configuration may aid in the growth of the subsonic portion of the boundary layer and that it is this subsonic portion which is contributing to the backflux. Further studies of this nozzle configuration and perhaps other nozzles are required to fully understand the nature and consequences of the highly viscous resistojet flow.

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