Investigation of a Liquid-Fed 
Water Resistojet Plume

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ABSTRACT

Measurements of mass flux and flow angle were taken throughout the forward flow region of the exhaust of a liquid-fed water resistojet using a quartz crystal microbalance (QCM). The resistojet operated at a mass flow rate of 0.1 g/s with a power input of 330 Watts. Measured values were compared to theoretical predictions obtained by employing a source flow approximation. Excellent agreement between predicted and measured mass flux values was attained; however, this agreement was highly dependent on knowledge of nozzle flow conditions. Measurements of the temperature at which the exhaust condensed on the QCM were obtained as a function of incident mass flux.

INTRODUCTION

Recently, there has been renewed interest in resistojets capable of utilizing water as a propellant. The multipropellant resistojet baselined for Space Station Freedom will potentially use water as a propellant. Also, the commercially-sponsored, man-tended space platform recently considered for development, baselined water resistojets as the primary on-orbit propulsion. Resistojet thrusters have been successfully integrated into spacecraft dating back to 1965, and although water was a candidate propellant for the biowaste resistojets of the Manned Orbital Research Laboratory (MORL) proposed in the early 1970's, a liquid-fed water resistojet has not been flight tested.

Successful integration of the water resistojet requires an accurate assessment of the potential impact that the water vapor plume may have on the spacecraft operation and missions. Since water vapor is readily condensible, one impact of primary concern is the possible contamination of spacecraft surfaces due to mass deposition. Sensitive optical surfaces, solar arrays, and thermal control surfaces can be adversely affected by the deposition of even a few angstroms of water. Field of view interferences caused by environmental contamination are also a concern for spacecraft users. Other potential impacts which must be addressed include thrust losses, disturbance torques, or thermal loading due to plume impingement. The magnitude of these impacts are highly dependent on the spacecraft architecture.

To predict the potential contamination effects of a water resistojet propulsion system, the plume must be modeled analytically, and, where possible, verified experimentally. A complete analysis of the exhaust flow field requires a solution to the Boltzmann equation. With the advent of supercomputers, great progress has been made in obtaining approximate numerical solutions of exhaust plumes using methods such as the Method of Characteristics (MOC), Direct Simulation Monte Carlo (DSMC), and kinetic theory models. G.A. Simons presented a widely used source flow method for the prediction of rocket exhausts. This method accounts for the expansion of the supersonic portion of the boundary layer of the nozzle, along with the inviscid core. Plume properties are expressed in terms of conditions at the nozzle exit and in terms of the boundary layer thickness. As this method was primarily devoted to the prediction of high thrust rocket nozzles with very thin boundary layers, there was no provision for subsonic boundary layer expansion. This method has been successfully utilized in the past by Genovese to predict spacecraft/plume interactions. Agreement between values calculated for a hydrazine monopropellant thruster plume interacting with a solar array and actual flight data was good. Calia and Brook also found good agreement with mass flux measurements made at large angles from the plume centerline of a small-scale reaction control engine.

Experimental verification of any of the above-mentioned techniques in a ground-based facility is a difficult task as it is not possible to accurately simulate the space environment while the thruster is operational. However, meaningful plume data can be obtained in the forward region of the plume (downstream of the nozzle exit plane) at facility pressures less than 10^-4 Torr for condensable propellants with the use of cryogens such as gaseous Helium at 16 K (GHe) or liquid Nitrogen at 77 K (LN2). A number of diagnostic techniques for the measurement of plume properties are well established. Experimental studies of pure gas, conical nozzle expansions into hard vacuum have been made to investigate the effects of nozzle area ratio and lip geometry, facility pressure, propellant condensation, and inadequate cryopumping in the back flux region.

Preliminary investigations of the resistojet thruster plume have been reported by Zana, et al. They made a comparison between mass flux measurements taken with a QCM and predicted values using a modified version of Simons' method. Because the resistojet thruster is characterized by highly viscous flow in very small nozzle geometries, the method of Simons' was modified by Hoffman to account for the thick boundary layers present in the nozzle. The mass flux data were obtained in the exhaust of a laboratory model resistojet operating on unheated CO2 using a cryogenically-cooled quartz crystal microbalance (QCM). In order to avoid limitations in the dynamic range of the QCM, a small amount of H2O in the CO2 was used as a tracer of the actual flow field. Qualitative agreement between theoretical predictions and experiment was found in the forward flux region. Breyale, et al. conducted a similar investigation addressing the effect of nozzle geometry on the exhaust plume. Again, agreement between the modified Simons' method and experiment proved to be qualitative. Both studies indicated that the suitability of the modified Simons' technique for predicting the exhaust flow field of viscous, low-thrust nozzles was promising but further experimental data were needed.
The objective of this work was to experimentally map the exhaust flow field of a liquid-fed, water resistojet and identify potential plume effects on a spacecraft with the primary focus on contamination. A cryogenically cooled quartz crystal microbalance was used to obtain a mapping of mass flux in the forward flux region of the plume. Also, local deposition rates as a function of surface temperature were obtained at various locations in the plume. In addition, an analytical study using the modified Simons' method of analysis for laminar flow from Schlichting may be found in Refs. 11 and 17, respectively.

In the far field, rocket nozzle flow may be treated as though it originates from a point source. The plume structure, however, may be divided into two distinct regions: the region which originates in the inviscid core of the nozzle, and the region which originates in the supersonic boundary layer. Using continuity, the density at any point in the plume can be calculated in closed form based on conditions in the nozzle according to the following equation:

$$\rho/\rho^* = A(R'/r)^2 f(\theta)$$  

(1)

The density varies inversely as the square of the distance from the thruster, and is related to the centerline value by a function \(f(\theta)\). This angular variation is described by two different expressions. The first expression is applicable for angles less than \(\theta_o\), the limiting turning angle for the plume's inviscid core. In this part of the plume the density is modeled by a cosine power function:

$$f(\theta) = f(\theta_o) \exp [-\beta (\theta - \theta_o)] \quad 0 \leq \theta \leq \theta_o$$  

(2)

There is no provision for flow beyond the calculated limiting turning angle, \(\theta_o\). The plume normalization constant in equation (1) is calculated using the following expression which is a simplification based on inviscid theory:

$$A = \frac{1}{8} \left[ \frac{\pi}{2} \right]^{1/2} \left[ \frac{\pi}{\theta_o} \right]^2$$  

(4)

The limiting turning angle, \(\theta_o\), may be calculated with the following expression:

$$\theta_o = \nu_{max} \cdot \nu + \theta_{nzt}$$  

(5)

where \(\nu_{max}\) is the limiting expansion angle for a flow with an infinite Mach number, \(\nu\) is the limiting expansion angle for a flow with the nozzle exit plane Mach number, and \(\theta_{nzt}\) is the geometric nozzle half angle. The remaining parameters \(\theta_o\) and \(\beta\) are functions of the nozzle exit conditions and the boundary layer thickness:

$$\theta_o = \frac{\pi}{2} \cos^{-1} \left[ \frac{\delta_o}{r_e} \left( \frac{2 \cdot \delta_e}{r_e} \right)^{1/2} \right]$$  

(6)

$$\beta = \frac{\pi}{2} \sin \theta_o + \sqrt{\frac{\pi}{4} \sin^2 \theta_o + \kappa \cos \theta_o - 1}$$  

(7)

where \(\kappa\) is:

$$\kappa = A \left( \frac{r_e}{r_{lim}} \right) \frac{2U_{lim}}{U_{lim}} \left[ \frac{\delta_e}{2} \left( \frac{\delta_e}{r_e} \right) \right]^{1/2}$$  

(8)

and \(U_{lim} = \alpha U_{lim} \) and 0.5 \(\alpha\) \(\leq\) 1.0. The boundary layer thickness, \(\delta_e\), is calculated using a classical flat plate analysis for laminar flow from Schlichting.19

$$\delta_e = \sqrt{\frac{\mu_{x_e}}{U_e}}$$  

(9)
APPARATUS

Test Facility

The experimental investigation was conducted in Tank 5 of the Electric Power Laboratory at the NASA Lewis Research Center. The cylindrical vacuum chamber is 18 m long and 5 m in diameter. The pumping system consists of twenty, 0.8 m diameter oil diffusion pumps with four rotary lobe-type blowers and four rotating piston roughing pumps installed in parallel. The facility is also cryogenically pumped with two large cryopanels installed at one end of the chamber (Fig. 1). The panels were LN₂-cooled to temperatures less than 90 K prior to testing. This portion of the tank was separated from the remainder of the tank by an auxiliary baffle and movable louvers. These louvers were in the open position during operation.

The thruster was located 0.2 m from the tank wall and was oriented such that it exhausted along an axis perpendicular to the tank's major axis. Tank pressures were monitored at three different locations during operation using hot-cathode ionization gauges. During thruster operation the tank pressure ranged from 1x10⁻⁵ Torr near the cryopanels to 7x10⁻⁵ Torr directly across from the resistojet.

![Figure 1. - Tank 5 including resistojet and cryopanels](image)

Thruster

The water resistojet employed for this study was a first generation thruster developed during an on-going research program at the NASA Lewis Research Center. A complete performance characterization of this device was conducted by Morren and Stone.²⁰ Fig. 2 displays a cross sectional schematic of the resistojet. The major components of this thruster were fabricated from stainless steel, while the helical heating coil was constructed from an insulated nichrome wire. The converging-diverging nozzle had a twenty degree half angle, a throat diameter of 0.012 cm, and an expansion ratio of 100:1.

![Figure 2. - First Generation Liquid-Fed Water Resistojet](image)

Quartz Crystal Microbalance

Mass flux measurements were taken in various parts of the plume using a cryogenically-cooled quartz crystal microbalance (QCM). QCMs have been used in similar investigations of exhaust flow fields.¹⁴⁻¹⁶,¹⁸,²¹ The QCM is a simple intrusive diagnostic tool consisting of a matched pair of precision crystals which oscillate at 10 MHz. The two crystals are LN₂-cooled to temperatures sufficient to condense mass on one of the crystals (sensor crystal). The other crystal serves as a reference and is not exposed to the incident mass flux. As mass condenses on the exposed surface of a sensor crystal the frequency of the oscillation changes according to the following relationship:

\[ \Delta \omega = \frac{\Delta m}{(k)(\omega^2)} \]

where \( \omega \) is the natural resonant frequency of the crystal, \( k \) is a constant dependent on the crystal cut, and \( \Delta m \) is the change in mass. The difference between the two frequencies, the beat frequency, which is directly proportional to the incident mass flux, was monitored using a digital meter. Pertinent operating characteristics and dimensions of the QCM may be found in Table I.

![Table I - Characteristics of QCM](image)

PROCEDURE

The experiment was designed to map the plume produced by a liquid-fed water resistojet. The thruster was operated at a nominal mass flow rate of 0.10 g/s and a power input of 330 Watts. Additional performance data are given in Table II. The reported value of thrust is from measurements taken by Morren and Stone.¹⁸ Performance of this thruster was found to be stable and repeatable. In the current investigation, the mass flow rate, heater voltage, heater current and five internal temperatures were monitored routinely during operation.
RESULTS AND DISCUSSION

The QCM was used to experimentally map the plume produced by a liquid-fed water resistojet. The data were compared to theoretical predictions obtained using the modified Simons' method, and the sensitivity of the modified Simons' source flow approximation to selection of two critical plume parameters was considered.

In addition to rotary surveys, measurements were taken with the QCM at a fixed angular orientation. These measurements were taken along three radial lines originating from the center of the nozzle exit plane at angles of 0, 10, and 20 degrees from centerline. The QCM was moved to a position along one of the lines and oriented at an angle of 70 degrees with respect to the line (see Fig. 5). When the QCM was in position, LN2 flow was initiated and the sensor cooled. When the rate of collection stabilized, the mass flux was recorded. If the sensor crystal was not saturated after obtaining a stable mass flux reading the QCM was moved to a new position along the radial line (still oriented at a 70 degree angle with respect to the line) and additional mass flux measurements were taken. If the crystal was saturated, the heating/cooling cycle had to be repeated.

The mass flux measured by a rotary QCM has been found to exhibit a cosine variation about the streamline. By utilizing this relationship and only measuring a small component of the total mass flux, the limit in the dynamic range of the QCM could be avoided. Mass flux measurements taken at a known angle with respect to a particular streamline could be corrected to give the mass flux that would have been measured along the streamline at that location in the plume. Using this procedure, measurements were obtained as close as 35 cm on centerline from the thruster. The existence of this cosine variation centered about the direction of the radial lines was subsequently verified at a minimum of one position along each of the three lines by conducting a complete rotary survey. The uncertainty in any of the mass flux measurements was estimated to be within ±30 percent primarily due to the temperature dependence of the capture coefficient.

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QCM Measurements

As expected, the condensation temperatures were found to depend on the magnitude of the incident mass flux. Fig. 6 is a plot of condensation temperature versus the steady state mass flux measured at many different QCM positions and orientations. The variation is uniform and the results were repeatable. This result indicates that the amount of condensation of water vapor from a resistojet on sensitive spacecraft surfaces can be successfully addressed experimentally. By placing a QCM at the location of interest relative to the resistojet, surface temperatures below which condensation would occur can be determined.
randomly directed molecules was sufficiently low in changes, the molecules moving in the direction of the parallel alignment of the QCM surface normal with the cosine of the angle. The mass flux resulting from the measured profile in Fig. 7(a) the measured local flow angle molecules resulting from collisions. When the surface of streamline have a smaller projected area of the sensor crystal is aligned perpendicular to the flow direction of the plume nearest the LN2 cooled cryopanels resulted in a lower measured background mass flux. The difference in measured background mass fluxes taken on the side of the plume nearest the LN2 cooled cryopanels consistently resulted in a lower measured background mass flux. The difference in measured background mass fluxes to the thrust axis was indicative of facility interaction. During prolonged runs it became evident that a significant portion of the total amount of water exhausted into the vacuum chamber had been collected on the LN2 cooled cryopanels. Therefore, the differences in measured background mass fluxes reflected the existence of a density gradient along the length of the tank caused by an asymmetry in the pumping system with respect to the resistojet exhaust. Three ionization gauges placed at different locations within the vacuum chamber also verified the existence of a density gradient. The ionization gauge closest to the cryopanels consistently indicated a lower tank pressure (1x10^-5 Torr) while the resistojet was operating.

The variation in mass flux with angle is shown in Fig. 7(b) for a location in which the magnitude of the mass flux resulting from the directed molecules of the plume was approaching background values. The interaction between the directed molecules of the plume and the randomly directed molecules that have undergone collisions resulted in a cosine variation that approached the uncertainty of the measurements. The characteristic cosine variation was still evident, but the maximum measured mass flux was only 40 percent higher than the mass flux values measured perpendicular to the measured streamline of 45 degrees.

From the rotary surveys, the local streamlines were determined at each location by curve-fitting a cosine to the measured mass flux values as shown in Fig 7. The relative magnitude of the on-streamline mass flux and the direction of the streamline are plotted in Fig. 8. The magnitude of the mass flux and the flow angle on both sides of the thrust centerline were approximately equal indicating that the plume was symmetric. However, there was a variation in the background mass flux measured at 90 degrees to the streamlines on either side of the thrust axis. Measurements taken on the side of the plume nearest the LN2 cooled cryopanels consistently resulted in a lower measured background mass flux. The difference in the magnitude of the mass flux is a function of the thruster location in the tank parallel to the centerline were approximately equal indicating that the plume was symmetric. However, there was a variation in the background mass flux measured at 90 degrees to the streamlines on either side of the thrust axis. Measurements taken on the side of the plume nearest the LN2 cooled cryopanels consistently resulted in a lower measured background mass flux. The difference in the measured background mass fluxes taken on the side of the plume nearest the LN2 cooled cryopanels resulted in a lower measured background mass flux. The difference in measured background mass fluxes reflected the existence of a density gradient along the length of the tank caused by an asymmetry in the pumping system with respect to the resistojet exhaust. Three ionization gauges placed at different locations within the vacuum chamber also verified the existence of a density gradient. The ionization gauge closest to the cryopanels consistently indicated a lower tank pressure (1x10^-5 Torr) while the resistojet was operating.

The magnitude of the mass flux vectors determined from the rotary surveys reached a low of 1.3x10^-5 g/cm^2 s at a location 10 cm downstream of the nozzle exit and 33 cm off the centerline. The maximum mass flux measured at angles greater than 45 degrees from the thrust axis was 2.7x10^-6 g/cm^2 s. A background mass flux of 4.6x10^-6 g/cm^2 s was calculated based on the assumption of randomly directed ambient temperature molecules at a pressure of 7x10^-5 Torr. This pressure was measured with an ionization gauge on the tank wall directly opposite the resistojet. The differences between the calculated background mass flux and the measured mass fluxes also indicated that a significant density gradient existed in the vacuum chamber.

A consideration of these facility effects has been included because measurements of plume properties taken in vacuum facilities are strongly dependent on the ability of a facility to accurately simulate a space environment. It was
recognized that meaningful measurements could not be obtained in all regions of the plume in the facility used for these tests. Those measurements taken in lower density regions of the plume have a higher degree of uncertainty than those taken in higher density regions; however, no measurements were taken where facility effects were thought to predominate over the expansion process. Consequently, no data were obtained at high angles from the centerline (near 90 degrees).

No rotary surveys were taken near the plume centerline because the water molecules from the exhaust condensed on the sensing crystal at such a rapid rate that the dynamic range of the device was quickly exceeded. In many cases the condensed layer of water molecules was so thick it prevented the crystal from oscillating at all. As previously mentioned, to avoid these limitations, the cosine relationship with rotary angle was employed. The QCM was oriented at a particular angle to a radial line and the measured value was corrected assuming the radial line was a streamline. The radial lines were experimentally verified to be streamlines by taking rotary surveys at a minimum of one point along each line. The resulting measured streamline angles determined along radial lines 0, 10, and 20 degrees relative to the thrust axis are included in Fig. 8.

Fixed angle mass flux measurements were taken along the plume centerline. The QCM was oriented at an angle of 70 degrees to the plume centerline. The centerline mass flux was then calculated assuming a cosine distribution centered at zero degrees. These values are presented in Fig. 9. A $1/r^2$ relation was fit to the experimental data. The small scatter in the data relative to the $1/r^2$ curve demonstrates the reliability of the QCM measurements.

**Parametric Analyses**

The modified version of Simons' method was used to obtain the number density distribution in the resistojet plume. As discussed previously, the density distribution in the plume is functionally dependent on several critical parameters which require a knowledge of conditions at the nozzle throat and exit plane. An accurate value of the neutralizing throat density is required for an absolute magnitude of number density in the plume. For this analysis, the throat density was based on a one-dimensional, isentropic analysis of the nozzle using the measured thrust and stagnation pressure to calculate a stagnation temperature at the throat. A throat density was then calculated from ideal gas dynamic relations. To account for real gas effects such as viscous dissipation in the nozzle, a 92 percent nozzle efficiency was assumed and the ideal throat density was increased by 8 percent for the analysis.

Fig. 10 displays the parametric sensitivity of the modified Simons' method to $\theta_m$, $\delta_e$ and $\alpha$ for a given set of conditions. The thruster nozzle exit plane is located at the origin. In the figures, the plotted contour represents a number density of $10^{12}$ molecules/cm$^3$. Marked differences in the calculated number density were observed for varied parameters holding all else constant. For example, the selection of the limiting turning angle is calculated from a knowledge of specific heat ratio and the Mach number at the exit plane (Eq. (5)). For the resistojet operating on H$_2$O with a $\gamma$ of 1.33, an exit plane Mach number of 6.1 was calculated from isentropic flow relations. This gives a calculated limiting turning angle of 74 degrees. However, previous experimental data indicates that the flow extends beyond the calculated limiting turning angle. This is characteristic of low Reynolds Number nozzle flows which have large boundary layers. Again, this analysis neglected the expansion of the subsonic portion of boundary layer. Fig. 10(a) presents number density contours for limiting angles of 74°, 105°, and 135°.

![Figure 10(a). Variation in $1.0 \times 10^{12}$ mol/cm$^3$ number density contour with the limiting turning angle, $\theta_m$.](image)

![Figure 10(b). Variation in $1.0 \times 10^{12}$ mol/cm$^3$ number density contour with the plume parameter, $\alpha$.](image)

![Figure 10(c). Variation in $1.0 \times 10^{12}$ mol/cm$^3$ number density contour with the boundary layer thickness, $\delta_e$.](image)

Similarly, the variations in density contours with the selection of $\alpha$ are shown in Fig. 10(b). Varying $\alpha$ affects the solution only in that portion of the plume resulting from the expansion of the boundary layer (angles greater than 31 degrees) since $\alpha$ affects the rate of exponential decay of the plume flow originating from the boundary layer through the parameter $\beta$ (Eq. (7)). The calculations displayed in Fig. 10(b) are for a limiting turning angle of 105 degrees. The model predicts that more flow will go into the backflow region with increasing $\alpha$.

The effect of boundary layer thickness was also investigated. This parameter determines the location of the
transition from core to boundary layer flow (Eq. (6)). It also controls the rate of exponential decay in the plume flow originating in the boundary layer through the parameter $\beta$. In this analysis, the boundary layer thickness was determined using a flat plate analysis and was calculated to be on the order of 25% of the exit area. Number density contours were calculated for boundary layer thicknesses twice the calculated value and one half the calculated value. The variation in the calculated contours is shown in Fig. 10(c) for $\alpha = 1.0$ and $\theta = 105$ degrees. These calculations show that the model is not sensitive to the value of $\delta$ for the given flow conditions.

The above discussion implies that the selection of $\alpha$ and $\theta$ is critical in comparing theory and experimental values. These functional dependencies also indicate that measured values in the plume can provide insight into conditions at the nozzle exit plane.

Comparison of Model with Experiment

A comparison of the experimental values of mass flux and those from the analyses is made in Fig. 11. The dashed lines in the figure were generated from a linear interpolation scheme of the measured mass flux. The solid lines in the figure were determined based on number densities calculated using the modified Simons' method and values of the critical plume parameters which gave the best agreement with the experimental values. Conversion of the calculated number density values to mass flux requires the particle velocity. The calculated limiting velocity was chosen. This velocity was calculated assuming the nozzle flow expanded to zero static pressure. The limiting velocity used to convert the calculated density to mass flux was 1660 m/s. The difference between the gas velocity based on measured specific impulse and the calculated limiting velocity was less than one percent. The values of all variables used in the analysis are listed in Table III. The agreement between the measured and calculated values is excellent.

![Figure 11. Measured and Calculated Mass Flux Contours](image)

Table III - Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plume normalization constant, $A$</td>
<td>$9.76 \times 10^{-1}$</td>
</tr>
<tr>
<td>Nozzle throat radius, $R_e$</td>
<td>$3.8 \times 10^{-2}$ cm</td>
</tr>
<tr>
<td>Nozzle exit radius, $r_e$</td>
<td>$3.8 \times 10^{-1}$ cm</td>
</tr>
<tr>
<td>Limiting velocity, $U_{lim}$</td>
<td>1660 m/s</td>
</tr>
<tr>
<td>Limiting velocity in the boundary layer, $\bar{U}_{lim}$</td>
<td>1660 m/s</td>
</tr>
<tr>
<td>Ratio between $U_{lim}$ and $\bar{U}_{lim}$, $\alpha$</td>
<td>1.0</td>
</tr>
<tr>
<td>Plume parameter, $\beta$</td>
<td>5.69</td>
</tr>
<tr>
<td>Specific heat ratio, $\gamma$</td>
<td>1.33</td>
</tr>
<tr>
<td>Boundary layer thickness, $\delta$</td>
<td>$9.95 \times 10^{-2}$ cm</td>
</tr>
<tr>
<td>Angle to edge of boundary layer, $\theta$</td>
<td>44°</td>
</tr>
<tr>
<td>Limiting turning angle, $\alpha$</td>
<td>105°</td>
</tr>
<tr>
<td>Nozzle throat density, $\rho_e$</td>
<td>$3.85 \times 10^{-4}$ g/cm$^3$</td>
</tr>
</tbody>
</table>

The excellent agreement between the calculated values and the measured values indicate that the Simons' source flow approximation is a viable tool for predicting the exhaust from a liquid-fed water resistojet. The 105 degree limiting turning angle indicated that the plume expanded more than anticipated. This was the result of either backscatter from the forward portion of the plume, or a significant subsonic boundary layer that was neglected in the analysis, or a much lower exit plane Mach number than calculated. It must be stressed that experimental data are required to define nozzle conditions before accurate plume calculations can be made. In particular, the value of the exit Mach number is critical as it defines the limiting turning angle.

CONCLUDING REMARKS

This paper has presented an experimental and analytical investigation of the exhaust from a liquid-fed water resistojet. The resistojet was operated at a mass flow rate of 0.1 g/s with a heater input of 330 W. Mass flux measurements were taken throughout the forward flow field using a cryogenically-cooled quartz crystal microbalance (QCM). In consideration of the potential impact to sensitive spacecraft surfaces, the surface temperature at which water began to condense was determined as a function of the incident mass flux. Condensation temperatures between 168 and 186 K were measured at various locations in the plume.

Complete rotary surveys were also obtained with the QCM. As has been demonstrated with pure gas expansions into vacuum, a cosine variation was exhibited about the flow streamline. The relationship between mass flux and flow angle was employed to obtain data at higher density regions of the plume where the dynamic range of the QCM was exceeded. Data were taken at a known angle to an assumed streamline and corrected to obtain the appropriate value of mass flux. In total, QCM measurements were taken at over sixty locations in the plume on both sides of the thrust centerline. The resistojet plume was axisymmetric; however, the rotary surveys with the QCM indicated differences in the background levels of mass flux on either side of the plume centerline due to non-uniform pumping in the vacuum tank. Evidence of pressure gradients in the tank were documented with the QCM measurements and also with pressure gauges.

Finally, the mass flux data were compared to theoretical predictions based on a modified version of Simons' method. Excellent agreement between theory and experiment was attained, however, a careful selection of several critical plume parameters was required. The sensitivity of the calculated density contours on three plume parameters was discussed.

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**Abstract**
Measurements of mass flux and flow angle were taken throughout the forward flow region of the exhaust of a liquid-fed water resistojet using a quartz crystal microbalance (QCM). The resistojet operated at a mass flow rate of 0.1 g/s with a power input of 330 Watts.Measured values were compared to theoretical predictions obtained by employing a source flow approximation. Excellent agreement between predicted and measured mass flux values was attained; however, this agreement was highly dependent on knowledge of nozzle flow conditions. Measurements of the temperature at which the exhaust condensed on the QCM were obtained as a function of ident mass flux.