Plume Mass Spectrometry and Calorimetry with a Hydrazine Arcjet Thruster

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Abstract

Molecular beam mass spectrometry and plume calorimetry were used to measure the chemical composition, angular distribution, speed distribution, and heat flux in the far field plume of an arcjet thruster. The arcjet was operated with simulated hydrazine propellant at a background pressure of 1 millitorr. Time-of-flight spectra yielded speed distributions for N₂, N, H₂, and H as a function of angle θ relative to plume centerline. Absolute fluxes were obtained from the experimental relative flux distributions by normalizing to the total mass flow rate. Dissociation fractions for N₂ and for H₂ were 11% and 14% at the nominal flow rate of 46.4 mg/s and 1660 W of power. Molecules near the centerline had average speeds near 7.5 km/s with the high end of the distribution extending to 10-12 km/s. The N₂ speed decreased to 2.7 km/s at θ = 80°. At the nominal flow rate, N₂ and N accounted for 89% of the arcjet thrust, and the mass flux for both species decreased by a factor of 10⁴ between θ = 0° and 90°. The angular distributions of H₂ and H were much broader, with mass fluxes that decreased by less than a factor of 10 between θ = 0° and 90°. Other quantities derived from time-of-flight spectra were the momentum flux, kinetic power flux, average speed, translational temperature, and speed ratio. A calorimeter consisting of an instrumented copper disk suspended in the arcjet plume was used to measure the absorbed power as a function of angle. The centerline power flux of 2200-2800 W/sr was mainly convective, while at θ = 90° the absorbed power flux was 70-125 W/sr with roughly equal contributions from convective and radiative heating.

Introduction

Data Relay Test Satellites (DRTS) are being developed by Mitsubishi Electric Corporation and National Space Development Agency of Japan. Hydrazine arcjet thrusters manufactured by PRIMEX Aerospace Company (PAC) will be used on DRTS for north-south stationkeeping.¹² Four arcjets are mounted on the north panel of the spacecraft, and they are fired in pairs for approximately half an hour, three times per week to control the orbit inclination and right ascension. To assess the attitude disturbances, orbit perturbations, and thermal loading caused by plume impingement, the Aerospace Corporation performed lab measurements and mathematical modeling of the plume from the arcjet thruster. In addition to investigating the far-field plume using mass spectrometry, the near-field was examined by laser-induced fluorescence.³ The measurements allow optimization of Direct Simulation Monte Carlo input parameters (in particular, the chemical composition and temperature) and validation of the model for the DRTS application.⁴

Arcjet Operation

The MR 509-A/B arcjet was operated in a diffusion-pumped 30-m³ stainless steel vacuum tank as was done in our previous arcjet experiments,³ using a certified ultrahigh purity gas mixture containing mole fractions of 67.3% H₂ and 32.7% N₂ (nominally 2:1). Except for removing the catalytic gas generator, the arcjet thruster, power cable, and power processor were equivalent to DRTS flight hardware. The mass flow rate and inlet gas density were nearly the same for our mixture as for decomposed N₂H₄, but the inlet temperature was 300-350 K rather than 700-800 K. Decomposed N₂H₄ contains NH₃ in an amount that depends on temperature and pressure, but dissociation of NH₃ in the arc-heated nozzle means that it would be a minor constituent of plume. Based on previous measurements by NASA and PAC,⁵ the 2:1 H₂ + N₂ gas mixture at ambient temperature was expected to reduce the thrust and specific impulse by 2% compared with decomposed N₂H₄ at the same flow rate (e.g., 504 s ³⁄₄ rather than 514 s). The reproducibility and accuracy of the mass flow settings were better than ±1% (i.e., ± 0.5 mg/s at 50 mg/s flow rate). Tests were performed at four flow rates listed in Table 1; these conditions are representative of arcjet operation on the DRTS spacecraft.

Mass Spectrometry Apparatus

The thruster was mounted on a computer-controlled rotary platform for sampling the angular range out to 100° from centerline. As shown in Fig. 1, the rotation axis was aligned with the arcjet exit plane. A complete map of the plume velocity vector distribution in the far field for each species can be obtained from scans of the polar angle θ, provided that the flow is axisymmetric.

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Table 1. Operating parameters for the MR 509-A/B arcjet using a 2:1 mixture of H₂ + N₂.

<table>
<thead>
<tr>
<th>Flow rate (mg/s)</th>
<th>Facility pressure (mtoorr)</th>
<th>Arc voltage (V)</th>
<th>Arc current (A)</th>
<th>Thrust (mN)*</th>
<th>Specific impulse (s)*</th>
<th>Thrust power (W)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.1</td>
<td>0.79</td>
<td>102.3</td>
<td>16.2</td>
<td>220</td>
<td>524</td>
<td>565</td>
</tr>
<tr>
<td>46.4 b</td>
<td>0.85</td>
<td>105.1</td>
<td>15.8</td>
<td>230</td>
<td>514</td>
<td>580</td>
</tr>
<tr>
<td>49.6</td>
<td>0.91</td>
<td>109.1</td>
<td>15.2</td>
<td>239</td>
<td>503</td>
<td>589</td>
</tr>
<tr>
<td>62.7 b</td>
<td>1.17</td>
<td>120.5</td>
<td>13.8</td>
<td>278</td>
<td>462</td>
<td>630</td>
</tr>
</tbody>
</table>

* Beginning-of-life performance estimated from PRIMEX thrust stand data.  
b "Nominal" flow is 46.4 mg/s. "High" flow is 62.7 mg/s.

A key requirement for plume mass spectrometry is that the background pressure be low enough to achieve molecular flow conditions within the probe volume (120-200 mm from the exit plane). For background pressures above 10 millitorr, the arcjet plume would be significantly altered at distances beyond 20 mm from the exit plane, which would preclude the kinds of experiments performed here. During arcjet operation a background pressure of 0.8-1.2 millitorr was maintained by diffusion pumps having a combined speed of 75,000 liter/s for 2:1 H₂ + N₂ (measured at cold flow). For a gas temperature of 293 K, the mean free path at 1 millitorr is 46 mm for pure N₂ and 90 mm for pure H₂, from which we estimate a mean free path of 75 mm for a 2:1 H₂ + N₂ mixture at 293 K. The mean free path of high-speed plume molecules at 1 millitorr background pressure is expected to be 150-200 mm (rather than 75 mm) because the scattering cross section decreases as molecular velocity increases. All data for MELCO were recorded with the skimmer orifice 127 mm downstream of the arcjet exit plane, so that the plume was sampled under conditions that approximated free molecular flow, and the data were representative of on-orbit conditions.

To dissipate the major portion of the plume heat load, a water-cooled copper plate covered the bulkhead on which the skimmer was mounted. The chopper wheel had four 1.6-mm wide slots and was rotated at 200 rev/s, giving a nominal shutter duration of 23 μs. Plume molecules were detected by an Exrel quadrupole mass spectrometer (QPMS) equipped with an electron-impact deflector ionizer and a channel electron multiplier. The multiplier output was sent to a current preamplifier having a sensitivity of 10⁻⁷ A/V and a rise time of 10 μs. Waveform averaging of the time-of-flight (TOF) spectra for up to 10⁶ shots enhanced the signal-to-noise ratio at a given angle.

To improve the detection sensitivity for H and N atoms, an electron-impact energy of 20 eV was chosen to minimize the extent of dissociative ionization (i.e., H₂ → H⁺ + H and N₂ → N⁺ + N). The mass spectrum in Fig. 2 was recorded while admitting a small amount of the propellant mixture into the mass spectrometer through a leak valve. Here the N⁺ production from N₂ is negligible compared to N₂⁺, and the H⁺ / H₂⁺ ratio from ionization of H₂ is only 1%. The spectrum in Fig. 3 was measured on the arcjet plume centerline using molecular beam sampling; it displays an H⁺ / H₂⁺ ratio of 9 %, along with signals at 14 (N), 15 (NH), 16 (NH₂), and 17 amu (NH₃) that were absent in Fig. 2. No time-correlated signal was seen at 17 amu when the wheel was spinning, and therefore NH₃ was not a detectable constituent of the plume. However, the presence of

Figure 1. Schematic diagram of the molecular beam mass spectrometer for measuring angular and speed distributions of plume molecules.
Mass spectrum of the 2:1 \( \text{H}_2 + \text{N}_2 \) gas mixture using a leak valve to bleed the sample into the mass spectrometer vacuum chamber. A background spectrum measured with the flow off was subtracted from the data.

Mass spectrum measured on the arcjet plume centerline using molecular beam sampling with the chopper wheel in the open position. A background spectrum measured with the flow off was subtracted from the data.

time-correlated signals at 1, 14, 15, and 16 amu (in addition to the demonstrated minimal extent of dissociative ionization) proved that the sampling system could detect \( \text{H}, \text{N}, \text{NH}, \) and \( \text{NH}_2 \) in the plume.

The speed distribution of a collimated supersonic molecular beam is conventionally represented by

\[
\frac{df}{dv} \propto v^3 \exp \left[ -\frac{M(v-v_e)^2}{2RT_s} \right].
\]  

This applies to an idealized flow at the skimmer orifice that has a three-dimensional Maxwellian speed distribution at the stream temperature \( T_s \) superimposed on the stream flow velocity \( v_e \).

\( df \) represents mass flow per steradian (i.e., mass flux) in the speed increment \( dv \), while \( R \) is the gas constant \( (8.314510 \text{ J mol}^{-1} \text{ K}^{-1}) \) and \( M \) is the molar weight. The arcjet flow differed from this idealized case, but our final results were independent of the assumptions underlying Eq. (1), because we used the equation only for least-squares fitting and not for extracting the average speed or translational temperature.

Calibration of the speed measurements was performed by comparing TOF spectra for a cold flow of helium through the arcjet. A relatively short drift distance was chosen (583 mm from wheel to ionizer) to enhance the sensitivity and to enable the detection of plume species at high angles. As a consequence, it was necessary to account for the wheel shutter function when extracting the speed distribution from a TOF spectrum as follows. The molecular flux at the ionizer is assumed to be proportional to the mass flow per steradian \( df/dv \) at the skimmer as given by Eq. (1).

The output signal \( S \) from the HPMS is proportional to the number density at the ionizer, and hence \( S \) is proportional to molecular flux divided by \( v \). The TOF spectrum \( dS/dt \) is then given by

\[
\frac{dS}{dt} \propto \frac{dv}{dt} v^3 \exp \left[ -\frac{M(v-v_e)^2}{2RT_s} \right].
\]

This expression was convolved with the measured shutter function using fast Fourier transforms as part of the least-squares fitting routine. Fitting of each TOF spectrum to the convolved Eq. (2) yielded the parameters \( v_e \) and \( T_s \). The routine gave a very good representation of the data in most cases, as illustrated in Figs. 4 and 5.

Figure 4. Time-of-flight spectra for \( \text{N}_2 \) in the arcjet plume at 46.4 mg/s. Data points and the least-squares curves are shown at angles of \( \theta = 0^\circ \) and \( 50^\circ \).
Figure 5. Time-of-flight spectra for H2 in the arcjet plume at 46.4 mg/s. Data points and the least-squares curves are shown at angles of $\theta = 0^\circ$ and $80^\circ$.

Mass Spectrometry Results

TOF spectra for N2, N, H2, and H in the arcjet plume were recorded in 10° angular increments from $\theta = 0^\circ$ to $100^\circ$, and the data were converted to speed distributions. The area under the speed distribution curves as a function of angle (namely, the angular distribution) was multiplied by $\sin\theta$ to convert from flux per steradian to flux per radian for integration over the angular range. As a first approximation, this integral was proportional to the total flow rate of a given species in the plume. However, a correction factor was needed to account for the species-dependent apparatus sensitivity. Based on published data,10 N2 and N have equal cross sections for electron-impact ionization at 20 eV, as do H2 and H. Moreover, N2 and N were observed to have similar angular distributions, as were H2 and H. Therefore we assumed that N2 and N in the plume were detected with equal sensitivity ($S_{N2}$) and that H2 and H were detected with equal sensitivity ($S_{H2}$). Taking account of the propellant composition (67.3% H2 + 32.7% N2) and comparing the integrated angular distributions gave the sensitivity ratio $S_{H2}/S_{N2} = 0.629$ at 46.4 mg/s flow rate. The measured sensitivity ratio of the QPMS for ambient temperature gases was found to be $S_{H2}/S_{N2} = 1.48$, which means that the molecular beam sampling system enhanced the detection of N2 and N (relative to H2 and H) by a factor of 1.48/0.629 = 2.35. This was attributed to the larger source volume for H2 and H which gave greater non-paraxial velocity components at the skimmer and prevented a portion of the molecules from being detected.3 In other words, the angular resolution of the sampling system discriminated against molecules coming from the outer portion of the extended source volume.

Figure 6. Mass flux vs. angle for N2, N, H2, and H at nominal flow.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mole fraction</th>
<th>Dissociation fraction</th>
<th>Flow (mg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>0.257</td>
<td>0.109</td>
<td>36.0</td>
</tr>
<tr>
<td>N</td>
<td>0.063</td>
<td>–</td>
<td>4.4</td>
</tr>
<tr>
<td>H2</td>
<td>0.510</td>
<td>0.143</td>
<td>5.1</td>
</tr>
<tr>
<td>H</td>
<td>0.170</td>
<td>–</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Based on the foregoing, dissociation fractions were calculated from the integrated angular distributions, and species flow rates were determined from the known total flow of hydrogen and nitrogen, with the results for nominal flow listed in Table 2. The main difference between nominal flow and high flow was that the dissociation fraction of N2 decreased from 11% to 6%, as would be expected for a decrease in propellant specific energy (J/kg). However, the H2 dissociation fraction was 14% at both flow rates. A second data set was recorded at nominal flow that gave results similar to Table 3, with the addition of measurements for NH and NH2, which had mole fractions of around 1.5% and 0.5% respectively.

Integrating over the speed distributions yields the mass flow per steradian (i.e., mass flux) as a function of angle shown in Fig. 6 for N2, N, H2, and H. The angular distributions were very similar for N2 and N at a given flow rate, with the flux for both species decreasing by a factor of $10^4$ between $\theta = 0^\circ$ and $90^\circ$. In our previous measurements on the NASA modular arcjet with pure hydrogen propellant,5 the H2 mass flux decreased by a factor of $10^2$ between $0^\circ$ and $90^\circ$. However, in the present experiment with the 2:1 H2 + N2 gas mixture the flux of H2 and H decreased by less than a factor of 10 between $0^\circ$ and $90^\circ$. This
broadening of the H$_2$ angular distribution upon adding N$_2$ to the flow suggests that H$_2$ was scattered more strongly by the heavy species than by other H$_2$ molecules. Velocity slip between the two species means that lighter molecules tend to overtake the heavier ones, which causes the light species to be scattered over a wider angular range when the plume consists of a gas mixture. One can also view this as an example of diffusive mass separation, which was observed previously in free jet expansions at low Reynolds number.$^{11,12}$

To derive the momentum flux, average speed, translational temperature, and speed ratio, we consider the number density speed distribution at a distance $r$ from the source:

$$\frac{dn}{dv} = \frac{1}{M} \frac{df}{dr^2}.$$

(3)

The number density $N$ at a distance $r$ and angle $\theta$ is

$$N(r, \theta) = \frac{dn}{dv}.$$

(4)

The expectation value of $v$-to-the-$n$th-power is

$$\langle v^n \rangle = \frac{1}{N} \int_0^\infty dv \langle v^n \rangle dv.$$

(5)

The mass flux $f$, momentum flux $p$, and kinetic power flux $w$ at an angle $\theta$ are

$$f(\theta) = \frac{\alpha}{\beta} \int_0^\infty dv \langle \rangle,$$

$$p(\theta) = \frac{\alpha}{\beta} \int_0^\infty v^2 \langle \rangle,$$

$$w(\theta) = \frac{\alpha}{\beta} \int_0^\infty v^3 \langle \rangle.$$  

(6)

(7)

(8)

The net thrust $F$ is the integral of $p \cos \theta$ over the forward hemisphere:

$$F = 2\pi \int_0^{\pi/2} p(\theta) \cos(\theta) \sin(\theta) d\theta.$$  

(9)

The translational temperature $T_v$ is calculated by assuming the thermal energy associated with gas flow along the viewing axis is

$$\frac{1}{2} M T_v = \frac{1}{2} M \langle v^2 - \langle v \rangle^2 \rangle,$$

(10)

which yields

$$T_v = \frac{M}{R} \left[ \langle v^2 \rangle - \langle v \rangle^2 \right].$$

(11)

Error bars for the above quantities in Figs. 6-10 are estimated systematic uncertainties associated with the apparatus calibration. Statistical uncertainties from the curve fitting are generally much smaller.

Momentum flux is a key parameter for evaluating plume impingement, and it is plotted as a function of angle in Fig. 7. For $\theta < 40^\circ$ the momentum flux was dominated by N$_2$, while for $\theta > 50^\circ$ the main contributor was H$_2$. Momentum flux was around 1 N/sr on centerline, decreasing to $10^{-3}$ N/sr at $\theta = 90^\circ$. The net thrust for each species from Eq. (9) is listed in Table 3. Here N$_2$ contributed 78.5% of the net thrust at nominal flow and 84.5% at high flow, while the contribution of N dropped from 10.4% to 6.2% when the flow was increased. There was an 8%-9% contribution to net thrust from H$_2$ and less than a 2% contribution from H. Comparing our total thrust in Table 3 with the values derived from PAC thrust stand data indicates an overall accuracy of $\pm 10\%-15\%$. Of course, the main purpose of this experiment was not really to determine thrust, but to measure the plume chemical composition, angular distribution, and speed distribution.

<table>
<thead>
<tr>
<th>Species</th>
<th>Thrust (mN)</th>
<th>Thrust fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$</td>
<td>209 ± 31</td>
<td>0.785</td>
</tr>
<tr>
<td>N</td>
<td>28 ± 4</td>
<td>0.104</td>
</tr>
<tr>
<td>H$_2$</td>
<td>25 ± 4</td>
<td>0.094</td>
</tr>
<tr>
<td>H</td>
<td>4 ± 1</td>
<td>0.017</td>
</tr>
<tr>
<td>Total</td>
<td>266 ± 40</td>
<td>1.000</td>
</tr>
</tbody>
</table>

*Beginning-of-life performance estimated from PRIMEX thrust stand data.*

Figure 7. Momentum flux vs. angle for N$_2$, N, H$_2$, and H at nominal flow.
The kinetic power flux plotted as a function of angle in Fig. 8 provides a measure of the convective heat input on spacecraft solar arrays and thermal control surfaces. As in the case of momentum flux, N₂ was the main carrier of power flux for $\theta < 40^\circ$, and H₂ dominated for $\theta > 50^\circ$. The kinetic power on centerline was 3500-4000 W/sr, decreasing to 4-8 W/sr at $\theta = 90^\circ$. Total kinetic power and power fractions are listed in Table 4, showing a partitioning among the species that differs somewhat from Table 3 in that H₂ and H contribute more to the power flux than they contribute to thrust. The total kinetic power (here measured as 1007 ± 171 W) should in principle exceed the arcjet thrust power ($\frac{1}{2} F \rho \overline{V} = 580$ W from PAC data or 760 ± 230 W from our Table 4), because the thrust is reduced by divergence losses. However, it appears that there is an additional source of error in the power flux, most likely the measured speed which contributes a $v^3$ term in Eq. (8).

The average speed is plotted as a function of angle in Fig. 9, indicating that the velocity slip between N₂ and H₂ was only 0.2 km/s at $\theta = 0^\circ$, but this increased to 3 km/s at $\theta = 80^\circ$. The average speed of N₂ was 7.5 km/s on centerline and decreased to 2.5 km/s at $\theta = 80^\circ$. Changing from nominal flow to high flow caused the average speed for each species to fall off more rapidly with angle. Translational temperature is plotted as a function of angle in Fig. 10, showing values in the range of 1500-2500 K for N₂ and N, and 300-900 K for H₂ and H at nominal flow. The N₂ speed distribution was actually narrower than that of H₂, but because they had approximately the same average speed the N₂ temperature was 5-6 times higher than the H₂ temperature. Changing from nominal flow to high flow had the general effect of lowering the translational temperature, particularly at angles away from centerline.

<table>
<thead>
<tr>
<th>Species</th>
<th>Power (W)</th>
<th>Power fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>716 ± 122</td>
<td>0.711</td>
</tr>
<tr>
<td>N</td>
<td>105 ± 18</td>
<td>0.104</td>
</tr>
<tr>
<td>H₂</td>
<td>151 ± 26</td>
<td>0.150</td>
</tr>
<tr>
<td>H</td>
<td>35 ± 6</td>
<td>0.035</td>
</tr>
<tr>
<td>Total</td>
<td>1007 ± 171</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Figure 8. Kinetic power flux vs. angle for N₂, N, H₂, and H at nominal flow.

Figure 9. Average speed vs. angle for N₂, N, H₂, and H at nominal flow.

Figure 10. Translational temperature vs. angle for N₂, N, H₂, and H at nominal flow.
Calorimetry

The absorbed heat flux (convected plus radiated) was measured as a function of angle using a calorimeter suspended in the arcjet plume, as shown in Fig. 11. The tip of a stainless steel-jacketed type K thermocouple probe was embedded in a copper disk (31.7 mm diameter, 7.4 mm thick) located 586 mm from the arcjet exit plane. Given the disk mass of 51.377 g and a molar weight of 63.54 g/mol, the temperature-dependent heat capacity was

\[ C_{\text{disk}} = 17.43 + 0.00781 \ T \ (W \cdot s/K). \]  

Temperatures were measured at a resolution of 0.01 K and stored at 100 points per minute. The initial temperature-vs.-time baseline was recorded for at least 5 minutes with the arc off and the thrust at \( \theta = 100^\circ \) relative to the probe. After ignition of the arc, the rotary platform was moved through increments of 5° or 10° every 36 s, and the rising temperature was recorded at each angle until reaching \( \theta = -5^\circ \). The thrust was then rotated to \( \theta = 100^\circ \), the arc was turned off, and the final baseline was recorded for at least 5 minutes. A linear regression yielded the slope \( (dT/dt) \) at each angle, from which was subtracted a baseline slope interpolated between the measured initial and final values. The baseline slope ranged from \(-5 \text{ K/hr}\) to \(-20 \text{ K/hr}\), while the slope with the arcjet running ranged from \(+20 \text{ K/hr}\) to \(+950 \text{ K/hr}\). Multiplying the net slope by the heat capacity in Eq. (12) gave the power absorbed by the calorimeter.

The calorimeter measured the power absorbed by a copper disk in the arcjet plume as a function of angle. Figure 12 shows the power per steradian \( (dP/d\Omega) \) and the power per radian \( (dP/d\theta = \sin \theta \ dP/d\Omega) \) at the nominal flow rate with an input power of 1660 W. The power per steradian at angles greater than \( \theta = 30^\circ \) was at least a factor of 10 less than on centerline. On centerline \( dP/d\Omega \) was in the range of 2200-2800 W/sr, decreasing to 70-125 W/sr at \( \theta = 90^\circ \). Comparing the calorimeter data with the kinetic power flux derived from mass spectrometry (Fig. 8) indicated that the fraction of the power accommodated by the disk was 63%-69% at \( \theta = 0^\circ \). The kinetic power flux was 4-8 W/sr at \( \theta = 90^\circ \).

The absorbed power was mainly convective for \( \theta < 30^\circ \), while at higher angles the radiated power contributed significantly. A simple mathematical model of the radiated power from the MR-509 arcjet predicted values in the range of 45-65 W/sr for \( \theta = 30^\circ-100^\circ \). Therefore convective and radiative heating contributed roughly equal amounts to the measured power for \( \theta > 60^\circ \). When the flow rate was reduced from 46.4 mg/s to 43.1 mg/s, the absorbed power increased for \( \theta > 30^\circ \). This was evidently due to an increase in radiative heating, consistent with the inverse relation between flow rate and the apparent brightness of the arcjet body. However, the calorimeter power for \( \theta > 30^\circ \) increased for flow rates above 46.4 mg/s despite the reduction in radiative heating. Presumably this was because broadening of the H₂ and H angular distributions increased the fraction of the convective power accommodated by the disk. Another contributing factor was enhancement of convective heating by the background gas as the tank pressure increased.

Integrating \( dP/d\theta \) over the range of measurement gave a total absorbed power of 1200-1900 W, depending on flow rate. This may be compared with the expected thrust power of 565-630 W (Table 1) and with the total kinetic power of 1000 W determined by mass spectrometry (Table 4). Facility effects undoubtedly added to the power measured by the calorimeter, because the disk was exposed to a convective heat flux from the background gas in the tank. In addition, the distance between the disk and the exit plane (586 mm) was 2-3 times greater than the mean free path for plume molecules at 1 millitorr, which diminished the contribution of the direct flow relative to the background.
Acknowledgment

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References


[13] D.R. Stull and H. Prophet, JANAF Thermochemical Tables, 2nd ed. NSRDS-NBS 37 (US Dept. of Commerce, 1971) gives heat capacities for crystalline copper of 24.46 J mol⁻¹ K⁻¹ at 300 K and 25.43 J mol⁻¹ K⁻¹ at 400 K. Thus Cᵥ = 21.56 + 0.00966×T J mol⁻¹ K⁻¹ over the relevant temperature range.