Effects of Background Pressure on the NASA 173M Hall Current Thruster Performance

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Facility background pressure levels are known to affect Hall thruster performance. Simple ingestion and ionization of the background gases has been determined to be an inadequate explanation of increased thrust at higher background pressure. In this study, thrust and plume measurements of the NASA 173M Hall thruster were made over a range of pressures from ~3 × 10^{-6} torr to ~3.5 × 10^{-5} torr. Thruster performance was investigated as a function of discharge current, cathode location, cathode-to-main propellant flow split, and magnetic field. At the highest discharge current of 15 A, a reduction in thrust of ≤ 2.5% was detected as the chamber pressure was reduced to 6 × 10^{-6} torr. Thrust was observed to increase by more than 3% when the cathode was raised 6 inches above the thruster. The thrust increase from increasing the cathode position was not significantly affected by the background pressure. From plume measurements taken 1 meter downstream, the plasma potential and the electron temperature increased with lower background pressure and decreased with cathode distance from the thruster. The effect of the cathode location on the electron temperature profile became more significant at lower pressure. Both the plasma potential and the electron temperature decreased with a higher flow split to the cathode.

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I. Introduction

Test chamber background pressure has been shown to affect the performance of the Hall Current Thruster (HCT). This behavior has often been termed a "facility effect." Understanding the nature of facility effects is important so that thruster operation in space can be properly predicted based on ground-testing. A number of investigations of these effects have been performed[1-8] but the exact nature and degree of changes to thruster performance appears to be dependent on several factors including the thruster design and operating point. Recently, among other studies, work at The Aerospace Corporation has examined the effect of background pressure on the SPT-100 Hall Thruster[7] and the BHT-1500 Hall Thruster[8].

Although simple ingestion of the background neutrals as an effective propellant may contribute to an increase in thrust with increased background pressure, it has been shown that this cannot explain the magnitude of all observations. Several other mechanisms have been proposed that can also contribute to the observed facility effects. These mechanisms include changes in beam divergence and ion acceleration[7,8], changes in electron coupling (particularly at high current density) in the near-field plume[5] and changes in the discharge circuit associated with interaction with conductive chamber walls[6].

This study focused on the effect of background pressure on thruster performance. No attempt was made to examine discharge circuit effects, however, since the location of the cathode has been shown to affect performance, the position of the cathode was included in this work.

In this paper, the effect of chamber background pressure on the performance of the NASA 173M thruster over a variety of operating conditions will be described. These operating conditions include the discharge current and anode voltage, the cathode location, the cathode-to-main propellant flow split, and the magnetic field. A description of the Test Facility including the Test Chamber and the Test Diagnostics will be included in the next section along with details of the thruster design and operating points. Section III will include Test Results and Observations and, finally, a Summary and Discussion will be presented in Section IV.

II. Experimental Apparatus

The testing described in this paper was performed in The Aerospace Corporation EP2 facility. The thruster was installed on a support bracket without the cathode attached. The cathode was mounted separately to allow it to be raised above its nominal location. There were 2 test campaigns. The first testing used a Heatwave 250 cathode instead of the cathode normally used with this thruster. This limited the thruster discharge current (J_d) to ≤ 10 A. Thrust data were taken at 4 different power levels but no plume measurements were made. In the second set of tests, the thruster was operated with J_d = 15A and a discharge voltage (V_d) of 300 V. In this case, both thrust and probe measurements were taken. In addition, during this testing phase, Laser Induced Fluorescence (LIF) measurements and Voltage/Current (V-I) stability curves were taken but these data will not be presented here. The background pressure was in the range from 3.0×10^{-6} to 3.5×10^{-5} torr. All pressure readings reported here have been corrected by a scale factor of 0.348 for xenon relative to nitrogen.

A. Experimental Apparatus

A schematic of the Aerospace EP2 facility is shown in Fig.1. It has been described in detail elsewhere[7] and will only be discussed briefly here. The chamber is 2.4 m in diameter and 9.8 m long with a total of 10 cryopumps providing a xenon pumping speed of ~250 kl/s. There are 6 re-entrant cryopumps (2 behind the thruster and 4 in the beam dump region) and 4 cryotubs beside the thruster. Fig. 2 provides a photograph of the test set-up. The thruster was mounted on a thrust stand (described below). A Y-axis positioner (positive upward) was used to hold the cathode and allowed adjustment of its position above the thruster. The nominal location for the cathode, defined as Y=0", has the keeper orifice located 0.75" above the top edge of the thruster and 0.50" in front of the exit plane. The cathode is positioned at an inclination of 30° from thruster centerline. In addition to thrust stand measurements, a Langmuir probe was mounted on a turntable that was secured to the top of the chamber. This allowed angular scans 1 m downstream of the thruster exit plane.

A calibrated, internally mounted, ionization gauge (labeled "Internal IG" in Fig. 1) was used to measure the Test Chamber background pressure. The gauge was mounted on a tee with the entrance aperture facing in the same direction as the thruster exit plane ensuring that background neutrals would enter both the gauge and the thruster in a similar manner. The tee entrance aperture was located approximately at the 10 o'clock position when facing the thruster and ~10 cm behind the thruster exit plane. A photograph of the Internal IG is shown in Fig. 2b.

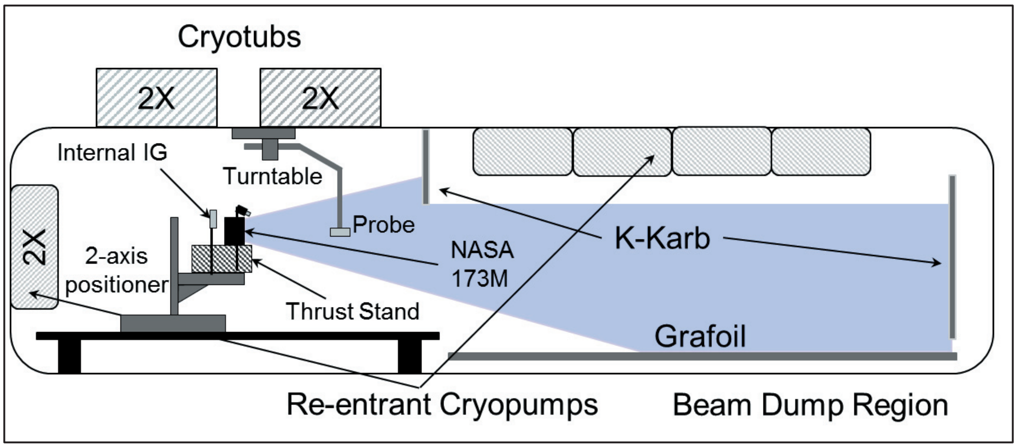

Figure 1. **Schematic of Aerospace vacuum facility. There are 2 ionization gauges (not shown) on the chamber wall. Pressures reported in this paper were measured with the "Internal Ionization Gauge (IG)."**

Changing the number of active pumps was the main way in which the background pressure was varied. By operating 2 pumps, 4 pumps, 6 pumps and 10 pumps, four pressure levels were obtained for these tests. During some additional tests with 10 pumps operating, the pressure was adjusted by injecting excess xenon through a port located on the centerline of the chamber, ~1.5 m downstream of the thruster.

B. Test Diagnostics

The primary diagnostics for this testing were thrust measurements made with the Aerospace thrust stand and plume measurements made using a Langmuir probe.

1. *Thrust Stand*

The Aerospace thrust stand is based on an inverted-pendulum[7]. It uses load cells for direct thrust measurement (Fig. 3). The sensing element of the thrust-measuring load cell ("thrust sensor") supported the pendulum against horizontal motion. A second load cell ("calibration sensor") was mounted behind the thruster, and was connected via nylon line and a spring to a stepping motor mounted to the stationary base of the pendulum. There is no temperature control with this thrust stand so there is a typical "drift" in the load as the temperature of the stand changes. The thrust stand and the thruster temperature were continuously monitored with thermocouples.

During this testing, thrust was measured in two ways. The first was termed "absolute", while the second was termed "relative". Absolute thrust measurements were made by recording the difference between thrust sensor outputs with the thruster on and off ("off" means no power or propellant flow). This measurement was followed immediately with a calibration of the thrust stand. Calibrations were performed with the thruster off by recording the response of the thrust sensor to a series of loads applied to the calibration sensor by applying tension to the spring. Typically 2 – 4 measurements were taken at each operating condition and averaged. Very small temperature drifts could be detected during the calibration phase and these were corrected.

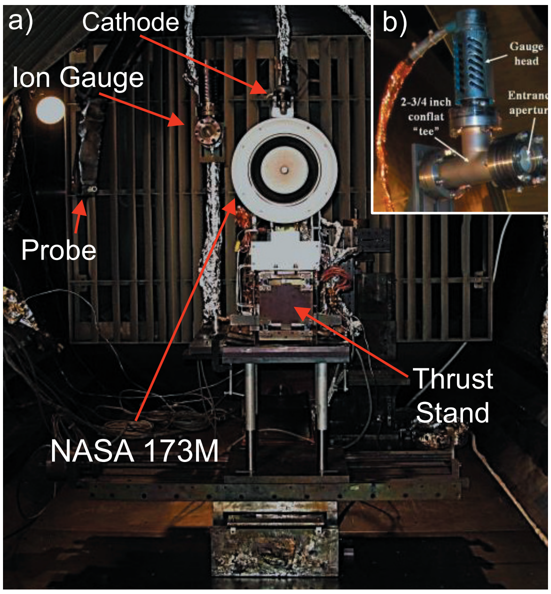

Figure 2. a) The NASA 173M HET mounted on the Thrust Stand on a 2-axis (x, z) positioner. The cathode is on a y-axis stage. b) A magnified view of the internal ionization gauge assembly.

Relative thrust measurements were made by changing the operating point while monitoring the thrust stand load. Several different operating points would be set during this period. The drifts due to temperature changes during the test period were corrected allowing the relative thrust change between operating points to be calculated. At the end of this sequence of testing an absolute thrust measurement would be made and the thrust stand would be calibrated. The absolute thrust measurement allowed conversion of the "relative" measurements to absolute.

2. Langmuir Probe

For these tests, a 0.5" planar probe was used. Current was recorded as the probe voltage was swept from -20 V to 20 V relative to ground in increments of 0.2 V. Plasma potential was identified as the voltage at which the slope of the current-voltage (I-V) curve attained its maximum value. The ion current collected at plasma potential was estimated by generating a linear fit to the ion-saturation portion of the I-V curve, and extrapolating to plasma potential. Electron current vs. voltage at or below plasma potential was obtained by subtracting the estimated ion current (from the linear fit) from the total current. Electron temperature was derived from the slope of a semi-logarithmic plot of the electron I-V curve, and electron density was obtained from the electron current measured at plasma potential using standard analysis methods[7].

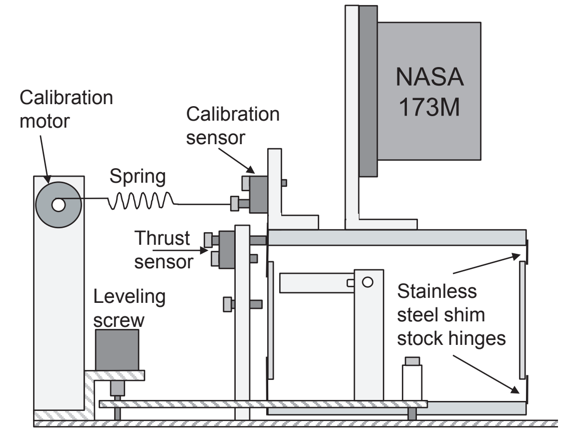

Figure 3. Aerospace Thrust Stand schematic.

C. The NASA-173M Thruster

The NASA-173M thrusters were designed and fabricated by the University of Michigan and the NASA Glenn Research Center (GRC). Several versions of the thruster were built and extensively tested[9,10]. The testing reported in this paper was performed using the NASA-173Mv2 thruster. The NASA-173M Hall thrusters were designed and tested to elucidate the underlying physics governing Hall thruster operation and performance and to help overcome design challenges associated with implementation of Hall thruster technology on NASA science missions. They are scaled for operation at a nominal discharge power level of 5 kW. The NASA-173Mv2 thruster is a single-stage thruster with a magnetic lens field topology. The thrusters' magnetic circuit consists of the magnetic poles, inner and outer electromagnets, and an internal trim electromagnet. The v2 thruster magnetic field topography was modified to leverage lessons learned during earlier test campaigns that provided insights on how the thruster performance at high specific impulse could be improved with an improved magnetic field topography. The thruster has an outer diameter of 270 mm and total length of 87 mm. The discharge chamber of the NASA-173M has an outer diameter of 173 mm, a channel width of 25 mm, and a channel depth of 38 mm.

The thruster was operated with laboratory power supplies. After thruster ignition, a 1.0-hour warm-up period was implemented prior to taking measurements. The facility conditions relevant to the thruster operation, including pressure, propellant flow rates, thruster and thrust stand temperatures, were continuously monitored and recorded.

III. Results and Observations

In the first phase of testing, thrust measurements were made at 4 power levels and 3 facility pumping speeds. The power settings were: 1.5 kW, 2.0 kW, 3.0 kW and 4.0 kW

In the second phase, a single thruster power level of 4.5 kW (J_d = 15 A, V_d = 300 V) was used and data were taken at 4 different background pressures, 2 cathode heights, 2 cathode-to-main propellant flow splits and 3 different current settings for both the inner and outer magnets. Absolute thrust measurements and plume measurements were taken at all four pressure levels, for both cathode heights and flow splits. Relative thrust measurements were made at all operating conditions. This represents a very large data set and only a sampling of it will be presented here.

A. Thrust Measurements

1. Thrust vs Pressure

The initial set of thrust measurements was taken using the Heatwave cathode ($J_d \leq 10$ A). It was located at the nominal cathode position of Y=0 in. with a cathode flow split of 10% relative to the main propellant flow. The inner (IM) and outer magnet (OM) currents were set to nominal values of 2.06 A for the IM and 2.60 A for the OM. The data were taken over 4 power levels at 3 different chamber background pressures determined by changing the number of operating cryopumps. As the pressure was varied, J_d was held constant. The results at P =1.5 kW (J_d = 5 A, V_d = 300 V) and 2.0 kW (J_d = 10 A, V_d = 200 V) are shown in Fig. 4 and at P = 3.0 kW (J_d = 10 A, V_d = 300 V) and 4.0 kW (J_d = 10 A, V_d = 400 V) in Fig. 5. With the thruster operating in this condition ($J_d \leq 10$ A), there was no change in thrust over the tested pressure range within the margin of error (± 2 mN).

The rest of the data from this testing were taken with the thruster operating at 4.5 kW with a constant discharge current of 15 A. In Fig. 6, thrust versus pressure data are shown for this operating condition. This figure includes averaged absolute thrust measurements taken at 4 chamber background pressures obtained by varying the number of active cryopumps and "relative" thrust measurements where the pressure was changed by adding xenon directly to the chamber. The conversion of the relative thrust measurement to absolute allows these 2 sets of measurements to be compared directly. The agreement between the 2 validates the use of the Internal Ionization Gauge to identify the chamber pressure conditions that affect the thruster performance.

Thrust measurements were made with the cathode at 2 height settings: Y=0" and Y=6". These data show thrust decreased by ~2.5% with a decrease in chamber pressure from 3.5 x 10^{-5} torr to 8 x 10^{-6} torr. In addition, Fig.6 shows that thrust increased by 7 to 8 mN (~2.8%) when the cathode was raised to a height of Y=6" above the thruster.

Changing the cathode flow fraction from 8% to 10% of the main propellant flow did not change thrust within the measurement uncertainty.

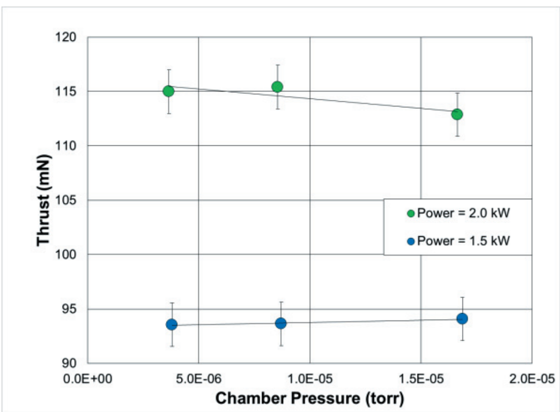

Figure 4. Thrust versus chamber background pressure at the 2 lowest power levels.

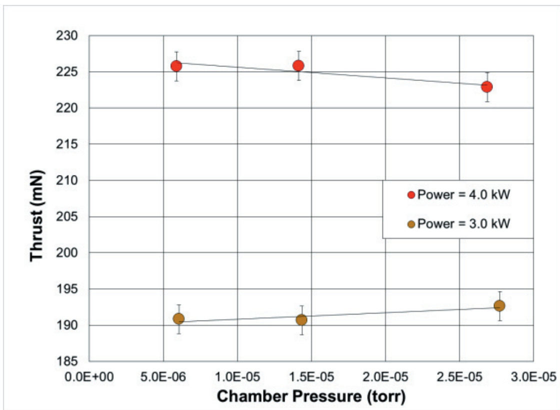

Figure 5. Thrust versus chamber background pressure with at mid-power levels.

2. Relative Thrust Changes vs Cathode Position

Detailed performance and plume measurements were taken at 2 cathode locations of Y=0" and Y=6". To examine the changes in thrust at in-between cathode locations, a set of "relative" thrust measurements was taken. These data and the corresponding cathode floating potential (with respect to ground) are shown in Fig. 7. The plasma potential (discussed later) at the 2 end points is also provided for reference.

In Fig. 7 the relative change in thrust can be seen to rise to a maximum as the cathode position approached Y=4". In this case, the thrust increased by ~5 mN compared to the 7 – 8 mN increase at Y=6" found previously (Fig. 6.)

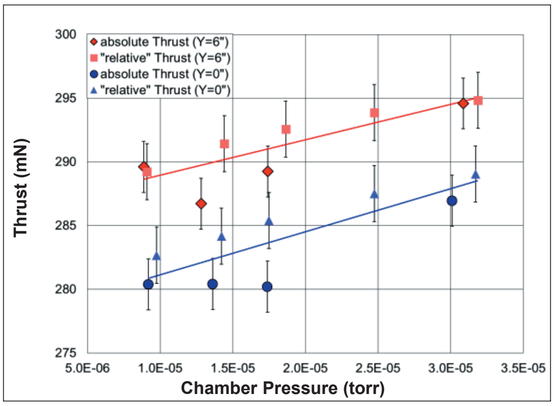

Figure 6. Absolute and "relative" thrust measured versus pressure at 2 different cathode heights. The thruster was operating at 4.5 kW with a constant discharge current of 15 A.

Other work has examined the effect of cathode location on the performance of a Hall thruster[11-17]. These studies have indicated that the cathode position relative to the magnetic field topology affects the coupling of the cathode electrons to the plume. In addition, the cathode coupling and thruster performance were improved by repositioning an externally mounted cathode to a central, on-axis location[5,14,15]. In cases where a separatrix is present[16,17], positioning the cathode inside the separatrix improved performance. It is interesting that while the NASA-173M has no separatrix the performance was observed to improve by increasing the distance of the externally mounted cathode from the thruster center-line.

3. Relative Thrust vs Magnetic Field

Relative thrust data were also taken at different magnet settings by varying the inner magnet (IM) and outer magnet (OM) currents. For the 173M thruster, the nominal IM current was 2.6 A and the nominal OM current was 2.06 A. Relative thrust measurements were made at these set points and at levels 0.6 A above and 0.6 A below those nominal levels. An example of the observed behavior is shown in Fig. 8. The changes in thrust due to the magnetic field changes were not dependent on the cathode height, the cathode propellant flow split or the chamber background pressure. The data shown in Fig. 8 are an average over all these test conditions.

From Fig. 8, there was an average increase of 1 mN in thrust when the OM current was increased by 0.6 A, however, there was a drop of 6 – 7.5 mN in thrust when the OM current was decreased by 0.6 A or the IM current was increased by 0.6 A. Decreasing the IM current by 0.6 A resulted in an average increase in thrust of 4 mN.

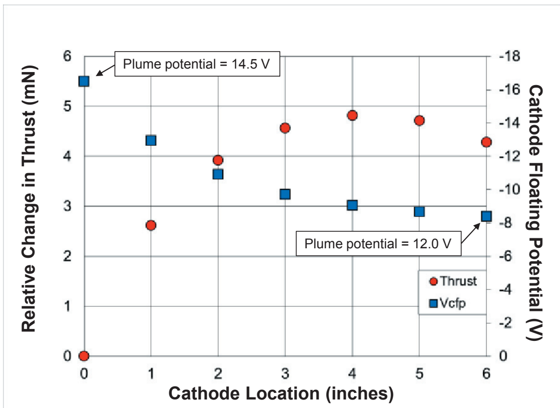

Figure 7. Relative thrust versus cathode height (in red). Matching values for the cathode floating potential (Cfp) relative to ground are also presented (in blue).

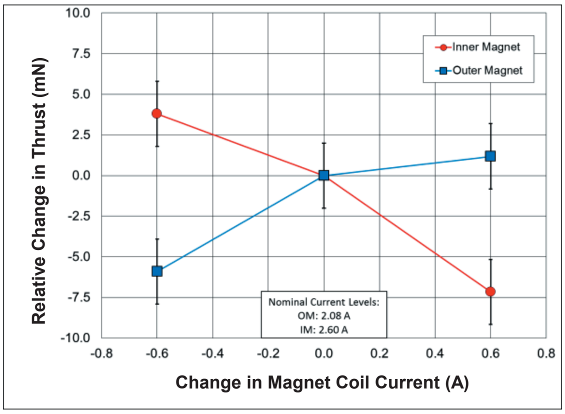

Figure 8. The effect of magnetic field changes on thrust. Thrust measurements were made relative to the nominal inner and outer magnet current settings.

When these magnetic field changes were made, the discharge current also changed slightly. No adjustment was made to the anode flow to maintain constant J_d during these measurements. The changes in J_d were small enough however that a plot of thrust/J_d vs magnet coil current resulted in no significant changes to the dependencies seen in Fig. 8.

The reason for these thrust changes with magnetic field has not yet been determined. The magnetic field was mapped inside and outside of the thruster channel for IM currents of 2.6 A and 2.0 A. The differences in the contour maps for the two IM current set points appeared small but are still being reviewed.

B. Probe Measurements

Langmuir Probe measurements were made at 49 angular locations for 16 different operating conditions. Measurements were made at 4 chamber background pressure levels (obtained by changing the number of operating facility cryopumps), 2 cathode locations (Y = 0" and 6") and 2 cathode-to-main propellant flow splits (8% and 10%.)

Analysis of the probe data provided values for the electron temperature (T_e), the electron density (n_e), and the plasma potential (V_p) in profiles across the thruster plume. These data are shown in Figs. 9 to 14 for the propellant flow split of 10%. In each plot, the profiles at each pressure level are shown. The profiles taken with the cathode at Y=0" are on the left side of the page and the profiles taken with the cathode at Y=6" are on the right side of the page. Estimated uncertainties for the Langmuir probe data are 0.2 V for plasma potential, 20% for electron temperature, and 30% for electron density.

The electron temperature profiles are shown in Fig. 9 and Fig. 10. An asymmetry in the T_e profile is apparent in these data with T_e rising from the left to right, facing the thruster. This phenomenon has been seen before with a different thruster in this facility. A facility issue, such as a gradient in the background pressure, may be responsible. In any case, it is observed that the asymmetry is more significant at lower chamber pressure and is reduced by increasing the cathode height to Y=6".

Figs. 9 and 10 clearly show that the electron temperature increased as the pressure decreased. This trend with pressure occurs at both cathode locations although T_e was lower with the cathode at Y=6". It was also observed that, across the angular profile, T_e was 0.2 – 0.3 eV higher when the flow split was at 8% as compared to 10%. While this shift in T_e is well within the measurement uncertainty, it was most noticeable with the cathode at Y=6".

Fig. 11 and Fig. 12 show the behavior of the electron density profiles. Although some scatter in the data points exists, it can be clearly seen that n_e, along the center of the profile (< 20°), decreased as the background pressure dropped. There was also a broadening of the electron density profile in the wings of the profile (> 20°) at the highest pressure level. Although the effect is small, it can be seen in these figures that n_e increased with the cathode at Y=6". Although not shown here, this increase was clearer at the lower cathode flow split of 8%.

The plasma potential profiles are shown Fig. 13 and Fig. 14. Here it is clear that the plasma potential increased as the background pressure dropped and decreased with the cathode height increased to Y=6".

Finally, although the trends with pressure were discussed above, plots of the on-axis values (averaged over the central 20°) of the electron temperature and the electron density are provided in Figs. 15 and 16. These plots very clearly show the dependence of these plume parameters on chamber background pressure and the impact of changing the position of the cathode from Y=0" to Y=6".

Cathode Height, Y=0”

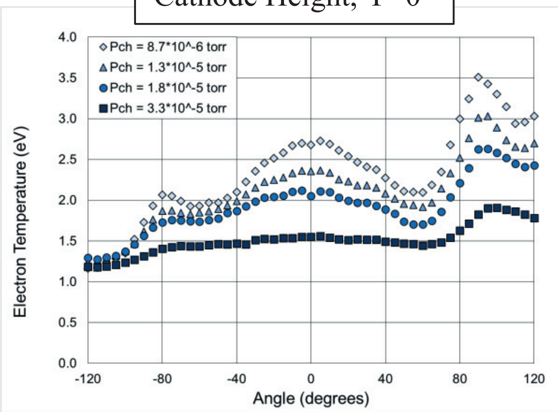

Figure 9. **Electron temperature over the range of chamber pressures. Y=0”.**

Cathode Height, Y=6”

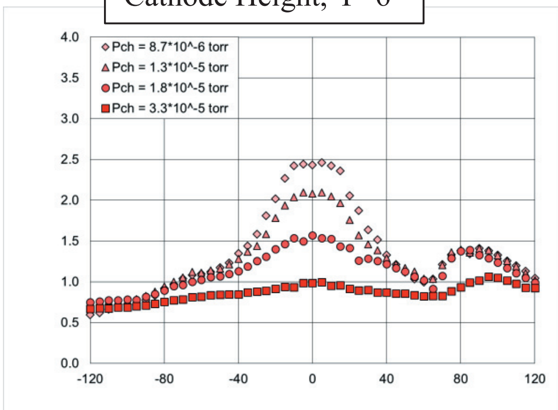

Figure 10. **Electron temperature over the range of chamber pressures. Y=6”.**

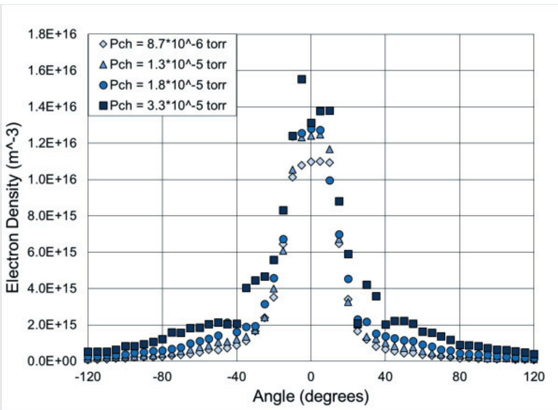

Figure 11. **Electron density over the range of chamber pressures. Y=0”.**

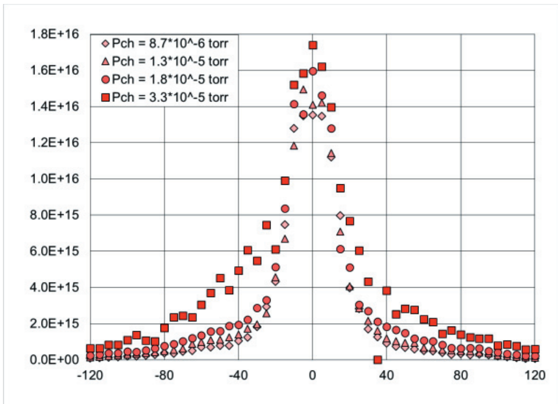

Figure 12. **Electron density over the range of chamber pressures. Y=6”.**

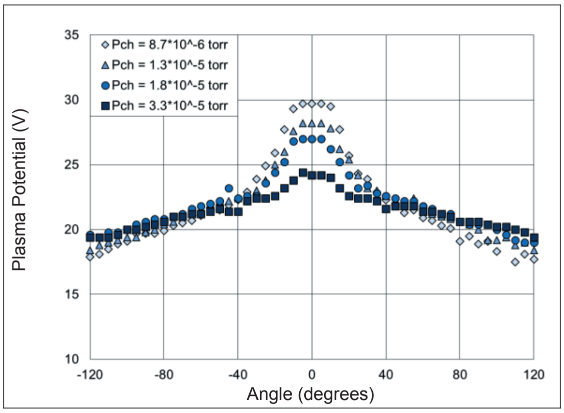

Figure 13. **Plasma potential relative to the cathode potential over the range of chamber pressures. Y=0”.**

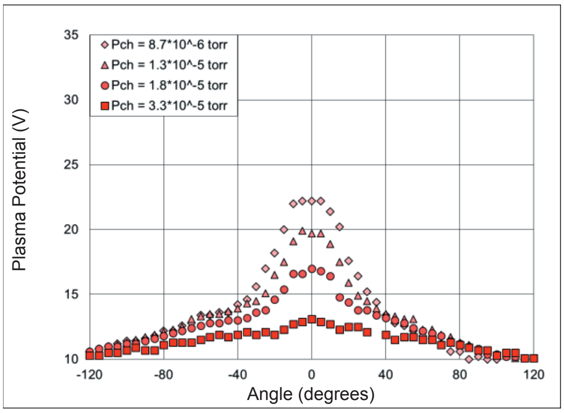

Figure 14. **Plasma potential relative to the cathode potential over the range of chamber pressures. Y=6”.**

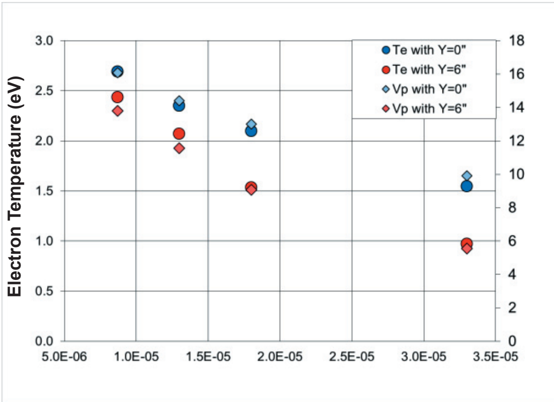

Figure 15. **Trend plot of the electron temperature and the plasma potential (relative to ground) versus chamber pressure along the central axis (theta = 0)**

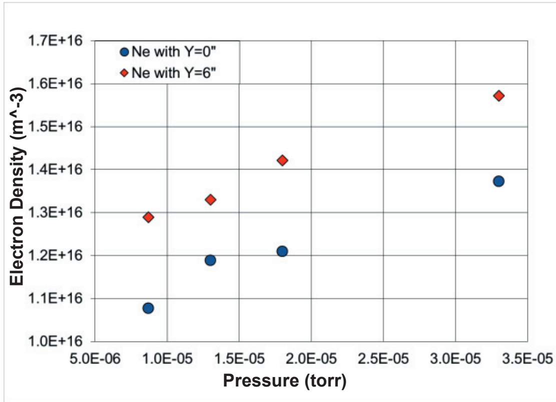

Figure 16. **Trend plot of the electron density versus chamber pressure along the central axis (theta = 0)**

IV. Summary and Discussion

The main purpose of this investigation was to characterize the sensitivity of the performance of the NASA 173M Hall thruster to background pressure. This was accomplished using thrust and plume diagnostics at different pressure levels determined by changing the effective facility pumping speed. Several operating points of the thruster were evaluated at these pressure levels. Variables included the cathode location, cathode-to-main propellant flow split, and magnetic field.

At low discharge currents (≤ 10 A), no effect was observed within the error of the thrust measurements. At a discharge current of 15 A, the thrust was seen to decrease by ~2.5% as the background pressure dropped from 3.5 x 10^{-5} torr to 8 x 10^{-6} torr.

Cathode location has been shown to be an important factor in both the performance of a HET[11-17] and potentially in eliminating the effect of chamber pressure on HET performance[5,8]. In this study, increasing the height of the cathode by 6 inches increased the output thrust by ~3% although the cathode location did not significantly change the performance sensitivity to pressure.

Changes in thrust with magnetic field were observed. Decreasing the IM current resulted in increasing thrust while decreasing the OM current caused an increase in thrust. These changes in thrust showed no dependence on chamber pressure, cathode position, or cathode flow split.

The probe data taken during this testing showed that the plume characteristics of the thruster were also affected by pressure and cathode position. The electron temperature and the plasma potential were observed to increase by ~40% on-axis as the pressure dropped from 3.5 x 10^{-5} torr to 8 x 10^{-6} torr, while the electron density decreased by ~30%. At the highest pressure tested, increasing the cathode height caused ~60% decreases in T_e and V_p. The effect of changing the cathode location on these plume characteristics was much less at the lowest pressure level tested, showing decreases of <15%. The effect of the cathode height on the plasma density was weak, showing increases of 10 – 15% when the cathode was positioned to Y=6".

The data from this testing supports the conclusions of other studies[7,8]. The increase in electron temperature with decreasing pressure did track the plasma potential exactly and this, in turn, may indicate changes in the acceleration region that could affect the thrust. It is unclear if this was a significant contribution to the observed changes in thrust. However, more importantly, the changes observed in the thrust and plume characteristics for the NASA-173M HCT at chamber background pressures below 2 x 10^{-5} torr supports the concern that the criteria for acceptable pressures for HCT testing need to be re-considered.

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