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Investigation into the Use of Cathode Flow Fraction to Mitigate Pressure-Related Facility Effects on a Magnetically Shielded Hall Thruster

Sarah E. Cusson*, Matthew P. Byrne†, Benjamin A. Jorns‡, and Alec D. Gallimore§
University of Michigan, Ann Arbor, MI, 48109

The ability to mitigate facility effects by varying the cathode flow fraction of a magnetically-shielded Hall thruster is experimentally investigated. The study is performed on a 9-kW class device operating on both internally and externally mounted cathodes. The cathode flow fraction is varied from 7 to 15% while the facility pressure is changed from background levels 4.5 to 25 μTorr-Xe. A thrust stand and a laser induced fluorescence system are employed to measure changes in performance and the location of the acceleration zone respectively. As has been found in previous studies, the thrust measurements show that the performance with the externally mounted cathode is more susceptible to neutral density changes than with the internally mounted cathode at the nominal cathode flow fraction (7%). The increase in facility pressure leads to a 7.1% change in thrust with the external cathode. When the cathode flow fraction is increased to 15%, the change in thrust is reduced 4.4% for the same facility pressure increase. The thrust for the internal cathode did not change measurably with facility pressure, however it increased 2.2% on average across all pressures by increasing the cathode flow fraction from 7% to 15%. This mitigation with cathode flow fraction occurs despite the fact that the additional xenon flow through the cathode only raises the background facility pressure by 2% compared to an entire order of magnitude change for the pressure studies. The ability for the cathode flow fraction to reduce the impact on performance of facility background pressure is discussed in the context of the local neutral density in the thruster exit plane. Laser induced fluorescence measurements show that the differences in thrust performance are linked to movement of the acceleration zone and that these shifts in acceleration zone asymptote with increasing neutral density in the thruster exit plane. As the cathode is a closer and more efficient source of neutrals, a small increase in cathode flow fraction is capable of saturating the exit plane with neutrals thereby minimizing the effects of the facility pressure increase.

Nomenclature

$f(u)$	=	ion velocity distribution function
L	=	discharge chamber length
$\dot{m}_a$	=	anode mass flow rate
P_d	=	discharge power
T	=	thrust
u	=	ion velocity
z	=	axial position

*Ph.D. Candidate, Department of Aerospace Engineering, and AIAA Student Member
†Ph.D. Candidate, Applied Physics Program, and AIAA Student Member
‡Assistant Professor, Department of Aerospace Engineering, and AIAA Senior Member
§Robert J. Vlasic Dean of Engineering, College of Engineering, and AIAA Fellow

I. Introduction

Hall thrusters are a form of electric propulsion that use crossed magnetic and electric fields to ionize and accelerate propellant. Their compact size combined with the ability to achieve a high specific impulse (> 2000 s) at high electrical efficiency (> 60%) have made them attractive forms of propulsion for several applications. Despite having decades of flight and development history[1], open questions remain about their operation. One of the most practical from a flight-development perspective is the phenomenon known as "facility effects." These are related to the known changes in thruster behavior that occur when moving from ground test facilities to in-space operation. This change is thought to be the result of non-vanishing background pressure and grounded facility walls. Previous studies have shown that all configurations of Hall thrusters are impacted by the facility, including thrusters with externally or internally mounted cathode and shielded as well as unshielded thrusters.[2–6] However, there is evidence that thrusters with externally mounted cathodes (as most systems currently flown have) are the most susceptible to these changes.[7] The ultimate implication is that there is a potential risk that thruster behavior could be sub-optimal or even unstable in orbit. This risk is compounded by the fact that the dependence of thruster operation on facility effects is not well-understood. This makes prediction of the transition from ground to flight particularly challenging.

While there are many known facility effects, one of the most critical, but least understood, is the response of the plasma's location in the discharge chamber to facility pressure. In Hall thrusters, the main ion beam is accelerated due to a potential drop between the anode and cathode. This drop occurs over a spatially small area (typically 1-10 mm), and its location is often coincident with the peak magnetic field. Previous studies have shown this location to be sensitive to facility pressure. For example, Nakles et al. found that the acceleration region moves axially upstream[4] with increasing pressure, which is correlated with a decrease in divergence angle. This should also correlate to an improvement in thrust. Similar trends in divergence angle have been noted in a number of pressure studies.[2, 3, 8, 9] More recently, the movement of the acceleration zone has taken on additional importance for magnetically shielded Hall thrusters where shifts in the region are thought to impact anomalous pole erosion of the thruster as well as the electron temperature of the grazing line.[10, 11]

Although the fundamental reason why the acceleration responds to pressure is still not understood, there have been a number of correlational insights into this effect. The first is that it appears that the movement in the acceleration zone (and therefore thrust) with facility pressure asymptotes. That is, the improvement in thrust will reach a plateau. As concluded by Hargus et al., the second insight is that it is the neutral density in the exit plane of thruster and not the actual facility background pressure that is the critical parameter driving the movement.[4, 12, 13] The potential implication from these two results is that it may be possible to re-create or even mitigate the movement of the acceleration zone (and therefore the change in thrust) if the neutral density in the exit plane is artificially raised. If a sufficient number of neutrals introduced to the channel from an external source connected to the thruster, the acceleration zone may be induced to reach its asymptotic limit. The facility increases thus will not have an effect. In order to test this hypothesis, we presented results showing that we were able to recover the trends in the movement of the acceleration region versus pressure simply by changing the cathode flow fraction (a proxy for total cathode flow).[14] A simple neutral model showed that the cathode was more efficient at delivering neutrals to the near-field of the discharge region resulting in similar changes in density in this region due to both effects. This work suggests that facility effects could be recreated by changing the cathode flow and that shifts in the acceleration region are driven by changes in neutral density in the same region.

Despite the insight that emerged from this previous work, we were not able to extend our conclusions about the movement of the acceleration zone to several practical facility-related effects. For example, this previous work was done on a centrally-mounted cathode. This is an issue for a few reasons: most current flight thrusters use externally mounted cathodes, back-up flight cathodes will inherently always be externally mounted, and externally mounted cathodes are more susceptible to facility effects. Additionally, the scope of the study was limited to just measurements of the acceleration region. Therefore, we were not able to show whether thrust and efficiency were impacted similarly and whether running a higher flow fraction mitigated susceptibility to facility effects. Thus, the goal of this paper is to close these gaps. We show thrust and acceleration region measurements for both internal and external cathodes and discuss the findings in relation to facility effects. In order to accomplish this, the paper is organized as follows: first, we discuss the experimental apparatus and test matrix used for this study. Next, we present the results and discuss the impact on our understanding of facility effects. Finally, we provide concluding remarks.

II. Experimental Apparatus

In this section, we present the thruster used in this experiment as well as the facility, diagnostics and test matrix.

A. Thruster

We used the H9 Hall thruster for this investigation. The H9 is a single-channel magnetically shielded Hall thruster developed by NASA's Jet Propulsion Laboratory in collaboration with the University of Michigan and the Air Force Research Laboratory.[15, 16] The thruster has a nominal operational power level of 4.5-9 kW. For this campaign, we operated the thruster at 4.5 kW, 300 V. Additionally, during this campaign, the thruster was in the cathode-tied electrical configuration.[17] We used two cathodes during this experiment, an externally mounted cathode and the nominal centrally-mounted cathode. Both cathodes use LaB_6 inserts with the external cathode having a nominal current up to 20 A and the internal cathode having a nominal current up to 60 A.[18] The external cathode was mounted at the 12 o'clock position on the thruster and angled towards the discharge chamber. A picture of the setup can be seen in Figure 1. The anode and cathodes were supplied with research-grade xenon through commercially available mass flow controllers. Power for the electromagnets and discharge was supplied with commercially available power supplies external to the chamber.

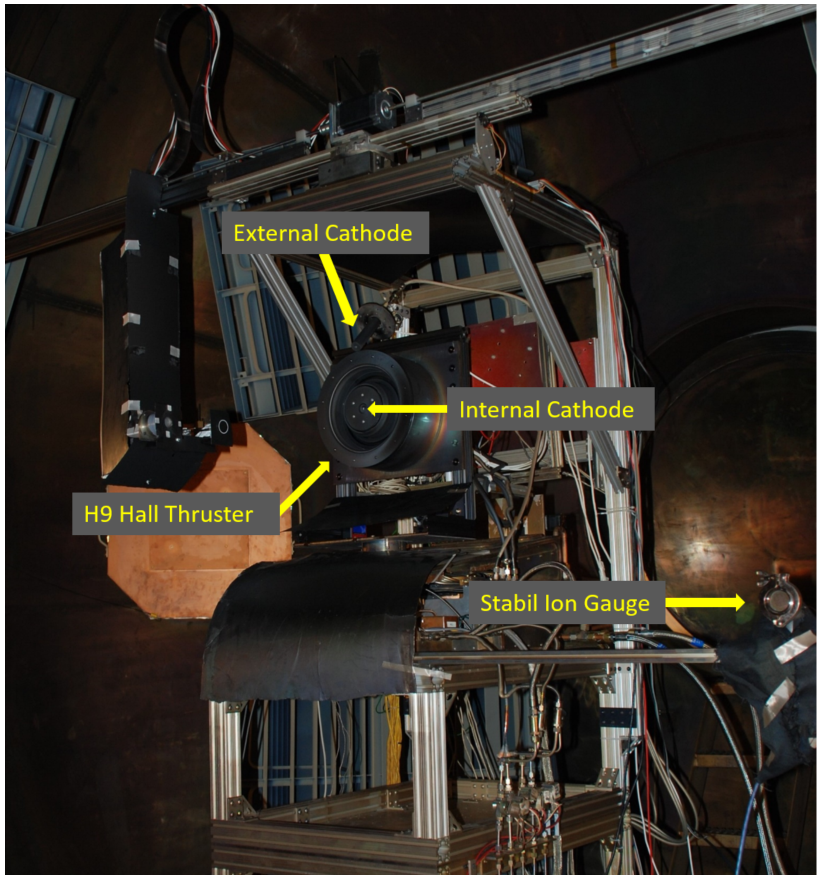


Fig. 1 The H9 Hall thruster installed in the LVTF at the University of Michigan with both an internally mounted and externally mounted cathode.

B. Facility

All testing occurred in the Large Vacuum Test Facility (LVTF) at the University of Michigan. LVTF is a 9 meter long, 6 meter diameter vacuum chamber with a base pressure of 0.5 μTorr-Xe. Nominally, the chamber is pumped with five cryosails and thirteen LN_2-backed cryopumps. Pressure was measured using a Stabil Ion gauge located approximately 1 meter away from the thruster in line with the exit plane as seen in Figure 1. The gauge has a grounded mesh attached to the entrance per industry standard. [19] In order to vary the background pressure during testing, a combination of a reduced number of pumps and downstream gas injection was used. For the downstream gas injection, the flow was introduced approximately two meters away radially and one meter downstream of the thruster with the flow injected axially away from the thruster to ensure that neutrals did not preferentially go towards the thruster.

C. Diagnostics

1. Thrust Stand

We used a water-cooled inverted-pendulum thrust stand to make thrust measurements.[20] The thrust stand operated in null mode with active inclination control. The thruster was run through an outgassing and warm up procedure before any measurements were taken. It then was operated for 15 minutes at a constant power before taking each thrust measurement. Inclination drift was accounted for in post-processing. Calibrations were performed by dropping a series of known weights. During the calibration, inclination was controlled. Analysis of thrust stand data indicated an uncertainty of 2%. All thrust numbers reported were "corrected" for power to the nominal 4.5 kW. The largest correction factor was 0.2%.

2. Laser-Induced Fluorescence

We characterized the acceleration region of the thruster by measuring the ion velocity using a standard, non-resonant laser induced fluorescence (LIF) technique that is commonly used in Hall thruster studies.[12, 14, 21] The setup used a tunable diode laser and taper amplifier to produce a laser beam with an output linewidth of less than 200 kHz. We targeted the $5d^4_{7/2} \rightarrow 6p^3_{5/2}$ metastable transition of xenon ions. To measure the velocity distribution, we injected the laser into the thruster plasma and swept the laser over a range of wavelengths (834.9 to 835.02 nm). We then recorded the intensity of the fluoresced light versus de-tuned wavelength by collecting the light with a fixed optic. The intersection of the injection optics and the collection optics, the "interrogation" volume, was 1 mm^3. The collection optics were placed approximately 60° off axis to better protect them from the main beam and allow for interrogation into the thruster.

Before injecting the beam into the thruster plume, we sampled it with a photodiode to measure the intensity and then sent it through a mechanical chopper to modulate the signal. We then collimated the beam and fiber-coupled it into the vacuum chamber. The optics were stationary during testing and the thruster was placed on two-dimensional motion stages in order to vary the interrogation point and generate a spatially-resolved map of the acceleration region. The light collected by the collection optics was sent out of the chamber and into a monochromator tuned to 541.91 nm. After the monochromator, the light was sent through a photomultipler tube, a trans-impedance amplifier and then measured using a lock-in amplifier. We then employed the Doppler conversion to determine light intensity versus ion velocity.

In order to analyze the recorded data, we start by normalizing the intensity to get the ion velocity distribution function (IVDF). We then take the first moment of the distribution to calculate the mean as,

$$u_{mean} = \int_{u_1}^{u_2} u f(u) du \tag{1}$$

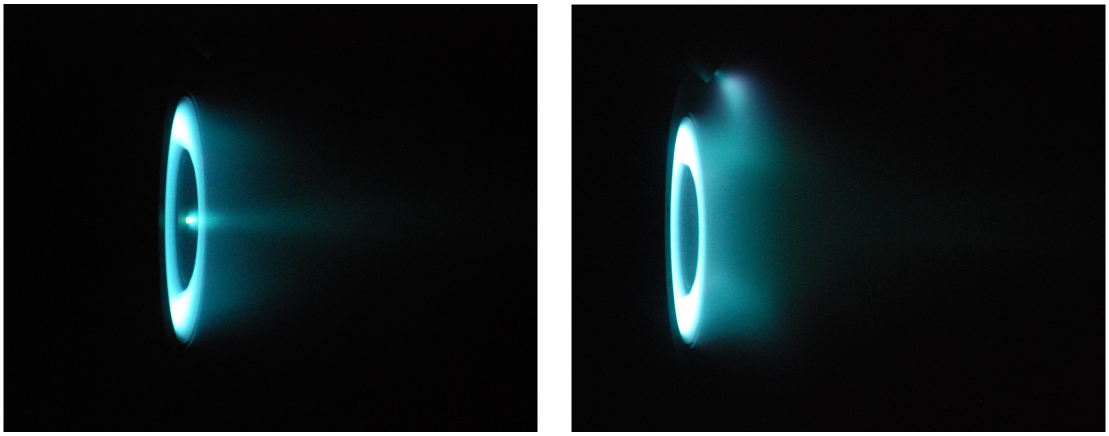
where u_1 and u_2 are the upper and lower bounds of velocity space. Next, we plot the mean velocity versus position to visualize the acceleration region. In order to compare conditions, we desire to quantitatively "locate" the acceleration region. In order to do this, we first fit a spline to the position versus velocity curve. We then take the numerical derivative of this spline resulting in a position versus electric field curve. Finally, we take the position of the acceleration region to be the location of peak electric field.

D. Test Matrix

We operated the thruster at ten different test points per cathode. The discharge voltage for the thruster was 300 V for all conditions and the discharge current was 15 A. The thruster was run prior to any measurements being taken in order to ensure the thruster was fully outgassed, the point at which oscillations and discharge current had reached steady-state values. The background pressure was varied from the base pressure of 3 μTorr-Xe to 25 μTorr-Xe linearly with five different test points. Additionally, the thruster was run at cathode flow fractions of 5%, 7%, 10%, 12.5% and 15%. During the experiment, the thruster was run in constant-power mode; we adjusted the flow to the anode with varying facility pressure to ensure that the discharge current remained constant at every test point.

III. Results

In this section, we first present the LIF measurements and then performance measurements. We discuss the results and their relation to facility effects and our previous work as we present them. Figure 2 shows the thruster operating

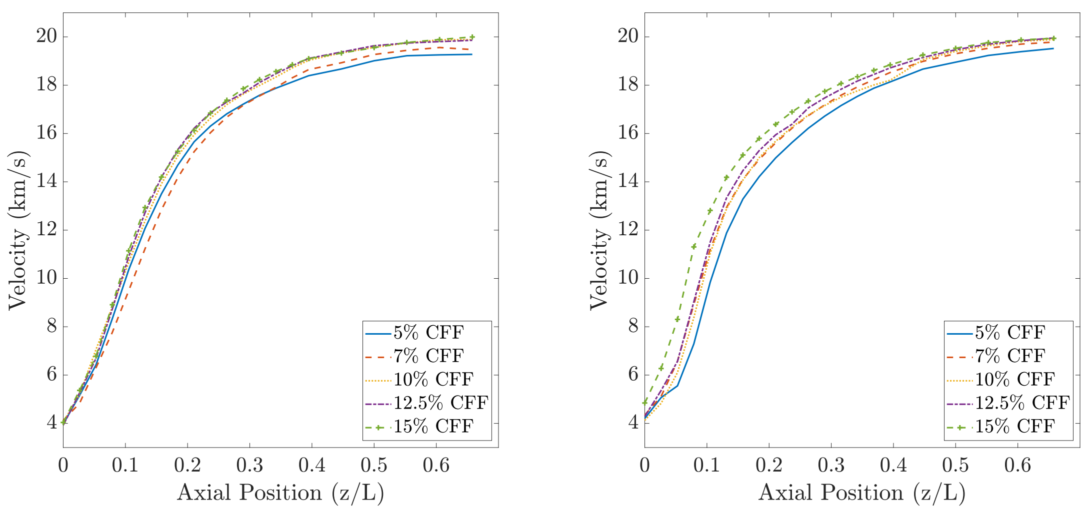


(a) (b)

Fig. 2 The H9 Hall thruster firing at 4.5 kW during this investigation using the internally mounted cathode (a) and the externally mounted cathode (b).

with both the internally mounted and externally mounted cathode. The plume structure is visibly changed significantly between the two different modes. This is an expected results and has been seen by others.[2, 7]

A. Laser Induced Fluorescence



(a) (b)

Fig. 3 Acceleration region measurements versus cathode flow fraction for both the internally mounted (a) and externally mounted (b) cathode.

Figure 3 shows the evolution of the ion velocity as a function of position for varying cathode flow fraction. Figure 3a shows this development for the internally mounted cathode while Fig. 3b shows this development for the externally mounted cathode. In general, our results demonstrate that the acceleration region shifts inward with increasing cathode flow fraction. This supports our previously published measurements on an internally mounted cathode.[14] Also, as expected, the externally mounted cathode appears to have larger shifts than the internally mounted cathode. Unlike our previous results, there does not appear to be a plateauing of the shift with varying cathode flow fraction for the externally mounted cathode. This is likely because the external cathode is more susceptible to these effects and the neutral density at which the trends plateau has not yet been reached. Figure 4 shows the location of the acceleration region (peak electric field) versus cathode flow fraction. The internal cathode shows a modest downward trend, however the location appears relatively constant. The external cathode shows relatively good agreement with the internal cathode results. There appears to be a larger downward trend with increasing flow fraction, again suggesting the external cathode is more susceptible to neutral density changes. Next, we look at the pressure study.

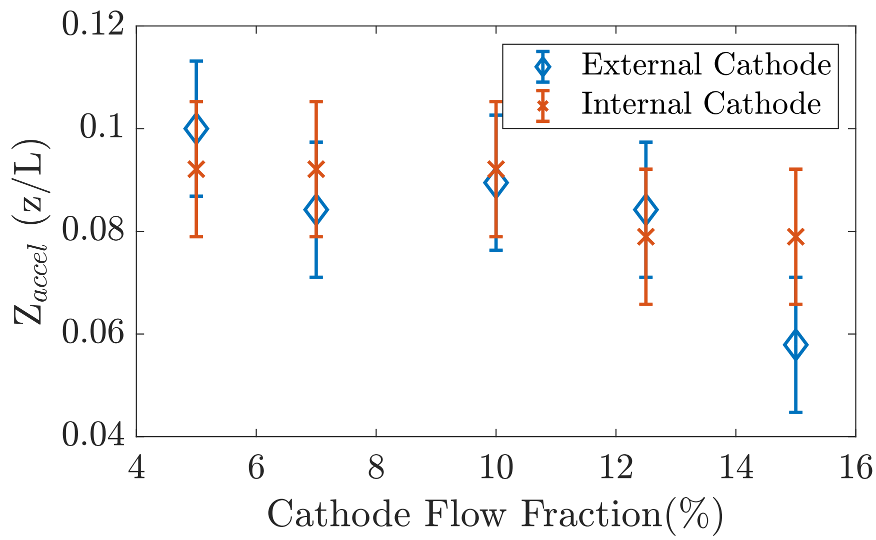
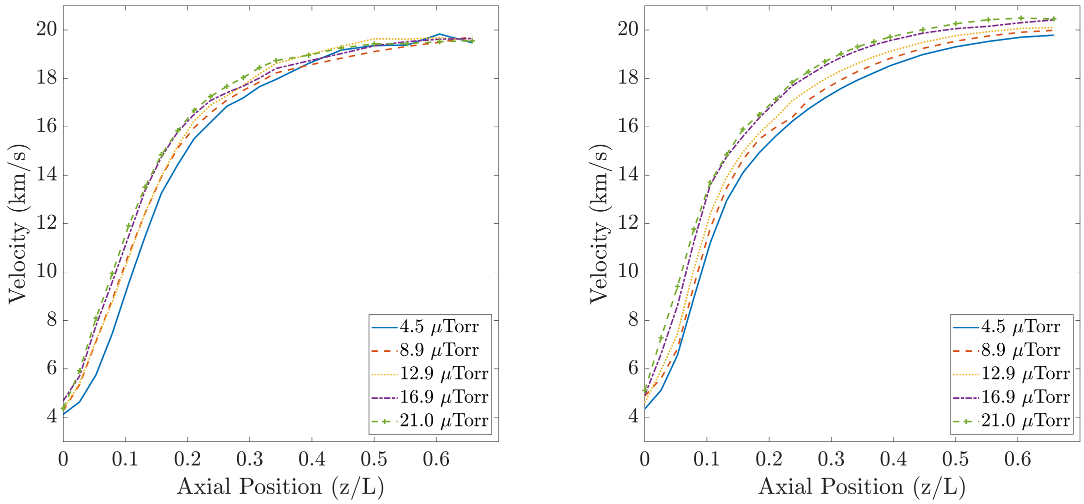


Fig. 4 Location of the acceleration region versus cathode flow fraction for both cathodes.

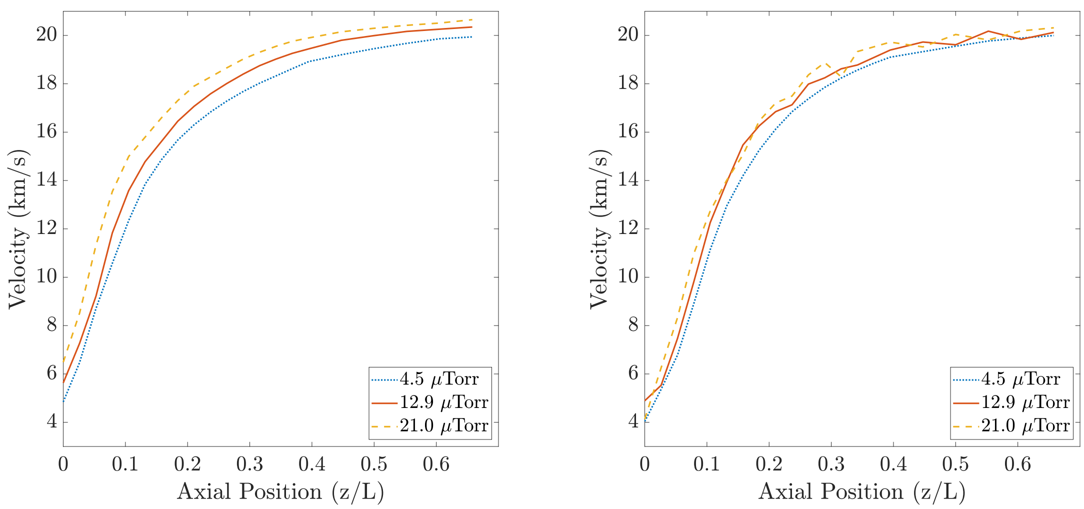
Figure 5 presents the visualization of acceleration region for each cathode with varying background pressure. We see similar trends as with the cathode flow fraction study. As the pressure is increased, for both cathodes, the acceleration region moves inwards. Again, the external cathode appears to be more susceptible to this effect than the internal cathode. Interestingly, it appears that the same downstream mean velocity is not reached for the ions during the external cathode pressure study suggesting that the accelerating voltage may be changing with pressure. It is difficult to know whether this is simply due to the extent of the measurement or not. If it is not, this suggests that in addition to the acceleration region shifting, there is a significant change in the cathode coupling voltage as well. As this is a parameter known to be impacted by the facility pressure, this appears to be a plausible explanation for our result. Interestingly, the cathode-to-ground voltage (a value used as a proxy for cathode coupling voltage) actually increased in magnitude with increasing pressure, from -19.7 V to -22.4 V. This change is small - less than 1% of the accelerating voltage suggesting that the same downstream mean velocity is likely reached.

Next, we look at the results from varying the pressure at higher cathode flow fractions. Our previous measurements suggest that an increased cathode flow fraction would reduce the susceptibility to facility effects. This would indicate that the shifting off the acceleration region would be reduced for varying pressure at higher cathode flow fractions. Figure 6 shows the results of this study. We see that for the internal cathode, there is essentially no shift in the acceleration region versus background pressure when the cathode flow fraction is increased. This indicates that the mechanism by which the facility neutrals are impacting the thruster is not a linear process and can be mitigated by changing the cathode flow fraction. The results for the external cathode still show the region shifting; this is not



(a) **(b)**

Fig. 5 Ion velocity versus position for varying background pressure for both the internally (a) and externally (b) mounted cathodes.



(a) **(b)**

Fig. 6 Ion velocity development as a function of position for the external (a) and internal (b) cathode versus background pressure when the cathodes are operating at 15% CFF.

unexpected as the “saturation density" was not reachable even at the highest cathode flow fraction for the external cathode. Thus a significantly higher cathode flow fraction would be needed to mitigate them.

Finally, similar to our previous work, we aim to determine the neutral density changes versus acceleration region for the external cathode. First, we model the changes in neutral density due to background pressure using the ideal gas law. We assume that the neutrals are thermalized to room temperature and calculate the neutral density using the measured pressure. We then subtract off the “base" condition in order to get the change in neutral density. We assume that this change is uniform throughout the vacuum chamber. We follow a similar procedure for changing cathode flow fraction; instead of assuming a uniform change throughout the facility, we assume hemi-spherical diffusive expansion from the cathode. We then look for the radius at which these two densities are of similar order of magnitude and find it to be approximately on channel centerline. Finally, we plot the change in neutral density on channel centerline versus acceleration region location.

The results of this calculation are shown in Figure 7. For modest changes in neutral density (up to about 4×10^{17} 1/m^3), we see an approximately linear inward trend versus changing neutral density. Once a sufficiently high change in neutral density is achieved, the trend begins to asymptote. This suggests that regardless of the source of the neutrals, a similar change in neutral density yields a predictable shift in the acceleration region location. These results also suggest that by increasing the external cathode flow fraction to 15%, we are not able to reach sufficient neutral densities to saturate the effect. Thus, we would need to increase this density even further for the external cathode to not cause shifts in the acceleration region. We now aim to correlate these results with thrust measurements.

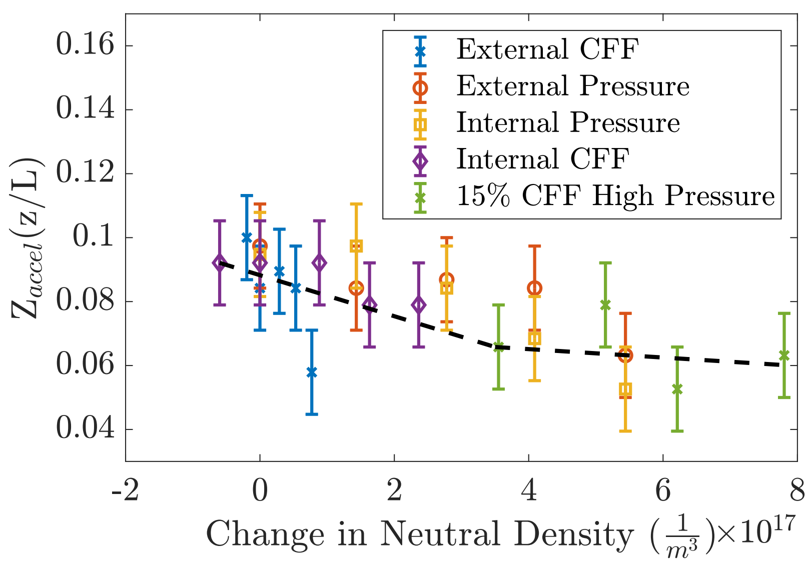


Fig. 7 Acceleration region location versus change in neutral density on channel centerline for the external cathode. "External/Internal Pressure" indicates the conditions in which the pressure was varied at 7% cathode flow fraction. Similarly, "External/Internal CFF" indicate the conditions during which the cathode flow fraction was varied. "15% CFF High Pressure" indicates the four conditions during which either cathode was operated at 15% cathode flow fraction and elevated background pressure. The black dashed line represents general trends.

B. Thrust Measurements

Figure 8 shows the thrust with varying cathode flow fraction. As expected, the thrust for the externally mounted cathode is lower than the thrust measured with the internally mounted cathode. This has previously been seen by Hofer et al. on both unshielded and magnetically shielded Hall thrusters. [2, 7, 22] Additionally, we find that from the lowest to the highest cathode flow fraction (5% to 15%) the thrust increases for the internally mounted cathode 4.5% while it increases for the externally mounted cathode 5.3%. This suggests that similar to background pressure, externally mounted cathodes are more susceptible to cathode flow fraction changes than the internally mounted cathodes albeit only slightly (and within uncertainty). This is more evidence that changes in the cathode flow rate can reproduce changes in facility pressure. Additionally, these results confirm that previous measurements[14] showing movement in the acceleration region with varying cathode flow fraction did indeed result in changes in thrust. Despite this increase in thrust, from an overall thruster perspective, while the anode efficiency ($T^2/[2\dot{m}_a P_d]$) increases with increasing flow

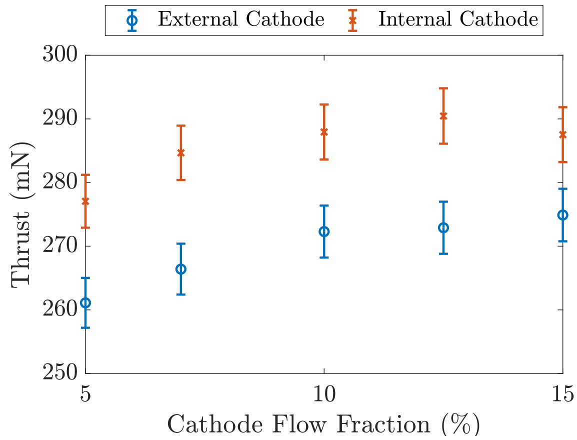
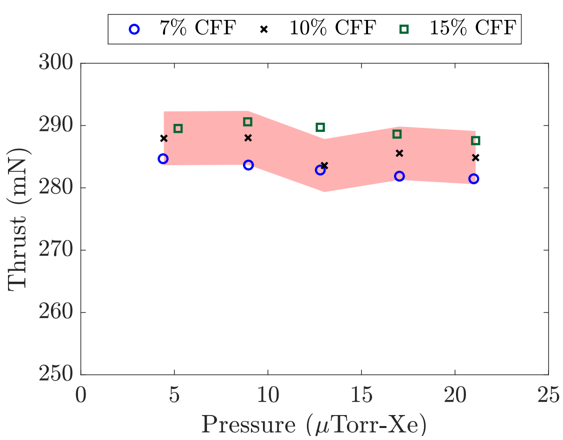


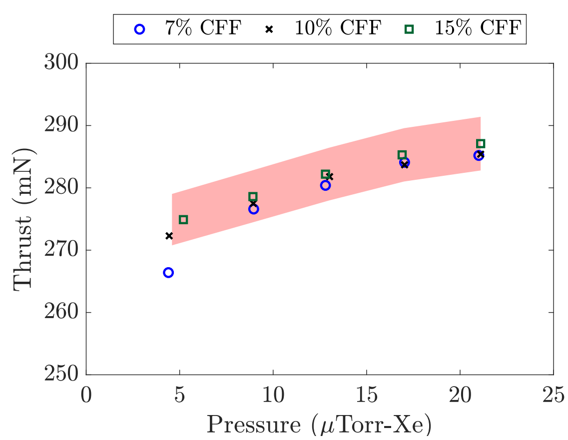
Fig. 8 Thrust versus cathode flow fraction for both the internally and externally mounted cathodes.

fraction, the total efficiency remains static due to the increased mass flow to the cathode.

Figures 9a and 9b show the data for three different cathode flow fractions (7%, 10% and 15%) with varying background pressures. The red shaded area is representative of the uncertainty for the 10% cathode flow fraction condition. As expected, the thrust is largely invariant with background pressure for the internally mounted cathode; however there is a slight increase with increasing cathode flow fraction. This increase is within the uncertainty of the measurement. Regardless, with the externally mounted cathode, the thrust increases with increasing pressure. This trend has been seen by others.[9] At the nominal 7% flow fraction condition, when the pressure was decreased from 21 μTorr-Xe to 5μTorr-Xe, the thrust decreased 7.1%. For the same reduction in pressure, when the cathode flow fraction was increased to 15%, the thrust only decreased 4.4%. This is a notable finding as we had previously suggested that increasing the cathode flow fraction would make the thruster less susceptible to pressure effects. The thrust measurements, in conjunction with the acceleration region measurements, confirm this correlation.



(a)



(b)

Fig. 9 Thrust versus pressure at three different cathode flow fractions for the internally mounted (a) and externally mounted cathode (b).

IV. Discussion

Nakles and Hargus previously showed increasing background pressure led to shifts in the acceleration region for an externally mounted cathode.[4] They also suggested that this could lead to changes in performance. However, their study was limited in scope to pressures between 10 and 30 μTorr-Xe. Thruster behavior is known to continue to change below these pressure levels.[9] Additionally, the study did not directly measure any performance data in conjunction with the acceleration region measurements. Regardless, first and foremost, our results here are consistent with theirs, showing that there is a shift in the acceleration region with increasing background pressure. As previously demonstrated by Hofer et al., we also show that the external cathode is more susceptible to these effects than the internal cathode.[2, 7] Most critically, for both cathodes, we show that the acceleration region of the thruster is moving axially and then correlate these measurements with performance, the critical parameter for many flight operators. Additionally, we show that by increasing the neutral flow in the cathode region, we are able to reduce the susceptibility of the thruster to facility effects. This is important for a few reasons: (1) it confirms that the internal and external cathodes have similar behavior with regards to acceleration region shifts versus neutral density changes in the same region, (2) these shifts lead to a measurable change in thrust and (3) there exists a way to mitigate these shifts by increasing the cathode flow fraction. While the results showed that we could not exactly recreate facility effects with the external cathode, we believe that this is because the same magnitude of neutral environment changes were not achievable with this cathode. If more neutrals were injected in this region (e.g. even higher than 15% cathode flow fraction), the results suggest that we would be able to saturate this effect. Additionally, this follows with Hofer's finding that the internal cathode is less susceptible to facility effects than externally mounted cathodes.[7] Because the internal cathode delivers neutrals more efficiently, the effect saturates faster thus allowing more constant performance for these cathodes.

Thus, on-orbit thrusters could mitigate outward shifts in the acceleration region and lower performance by increasing the cathode flow fraction. However, increasing the cathode flow fraction is known to reduce the cathode lifetime due to increased pressures in the insert region.[23]. Since the results show that this region is not critical to the effect and it is about effectively delivering the neutrals, a solution to this problem is to inject the additional neutrals via the cathode-keeper gap, similar to what high-current cathodes do to prevent high-energy ions.[24, 25] With this technique, an increased neutral density could be achieved at the thruster exit plane without sacrificing cathode lifetime. While the results here are compelling, we are unable to explain the changes in cathode-to-ground voltage. Our previous work directly measured the cathode coupling voltage[18] and actually found opposite trends in this value for the pressure study versus the cathode flow fraction study. Therefore, we do not believe this parameter to cause large impacts on performance.

V. Conclusions

The thrust and acceleration region of a magnetically shielded Hall effect thruster operating at 4.5 kW were measured for varying cathode flow fraction and background pressure. The measurements were taken with both an externally and internally mounted cathode. Previous experimental evidence suggested that increased cathode neutral density could impact the location of the acceleration region in a similar manner as increased background pressure. The results show that for the internally mounted cathode the thrust increased 4.5% by increasing the cathode flow fraction from 5 to 15%, however the internal cathode was largely insensitive to pressure. For the external cathode, the thrust increased 5.3% with cathode flow fraction and 7.1% with pressure. However, when the cathode flow was increased to 15%, the thrust only varied 4.4% suggesting increased cathode flow fraction reduces facility pressure effects. The acceleration region measurements largely supported the conclusion from the thrust data showing shifts in acceleration region for all cases with increased neutral density. Increasing the cathode flow fraction to 15% again decreased these shifts. All together, these data suggest that increased neutral density near the thruster exit plane drives changes in the acceleration region which are then traceable to changes in thrust. These changes can be mitigated by increasing the neutral flow in the cathode region suggesting a promising technique for flight operators to reduce the risk posed by changing conditions from ground facilities to orbit.

Acknowledgments

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