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ABSTRACT

The influence of the cathode flow fraction and facility background pressure on the acceleration region of a magnetically shielded Hall thruster is experimentally characterized. The location of the acceleration region is measured using laser-induced fluorescence on H9, a 9-kW class Hall thruster, for six different facility background pressures and four different cathode flow fractions. The results show that when the facility pressure is increased from 7.1×10^{-6} to 3.0×10^{-5} Torr-Xe, the acceleration region shifts inward 1.6 ± 0.5 mm. Similarly, when the cathode flow fraction is increased from 7% to 15%, the acceleration region shifts inward 0.9 ± 0.5 mm. This experiment leads to two conclusions. First, introducing neutrals in the cathode region can directly impact the acceleration mechanism in the thruster. Second, changing the cathode flow fraction affects the acceleration region of the thruster in a similar manner as the background pressure. This result is discussed in the context of the neutral density environment created by both injection schemes. Calculations of this parameter show that the increase in neutral density in the proximity of the acceleration region is similar when varying the background pressure and changing the cathode flow fraction. This provides correlational evidence linking the role of neutral density to the acceleration region shift.

I. INTRODUCTION

Hall thrusters, a type of electric propulsion using crossed magnetic and electric fields to accelerate ionized propellants, have decades of flight history on orbit.[1] Despite this extensive heritage, there are still a number of fundamental open questions about their operation. One issue of practical importance is the ground-to-flight transition where there is uncertainty as to whether ground testing results will translate to on-orbit operation. This ambiguity stems from the fact that thrusters are known to operate differently in the confines of a vacuum chamber on the ground versus in space. This discrepancy is thought to be largely a result of two effects: non-vanishing background pressure in test facilities and the presence of a grounded boundary changing the properties of the plasma discharge. These so-called "facility effects" have been widely characterized experimentally[2] with most thruster configurations, showing susceptibility to at least the effect of the background pressure variation.[3] In particular, it has been demonstrated experimentally that thrust, the acceleration region location, cathode coupling voltage, and oscillatory behavior all are impacted by changing pressure.[3–5]

The movement of the acceleration region with facility pressure has the potential to be particularly problematic. In Hall thrusters, the acceleration of the ionized propellant is the result of ions falling through a potential drop that is established between the upstream anode and the downstream cathode. This potential drop is precipitous, occurring over a very small region–1–5 mm spatially–along the thruster channel centerline.[6,7] Under nominal conditions, the location of this drop is usually coincident with the region of peak magnetic field strength.[8] However, it has been shown experimentally that the location of this acceleration region is susceptible to the background pressure.[5] The region will move upstream, further into the discharge chamber, with increasing facility pressure. This shift can have a number of marked effects on overall thruster performance including divergence efficiency, oscillations, and thruster-spacecraft interactions.[9–11] Because of these potential consequences and the fact that the background pressure shifts orders of magnitude from the ground to the orbit, there is a recognized and pressing need to understand the mechanisms that drive this change in the acceleration region location. However, despite a range of experimental studies, the reason why this shift occurs has been unresolved.

In this study, we explore the hypothesis that this facility effect may be related to the thruster cathode's susceptibility to facility pressure. Indeed, it has already been established from previous studies that changes in the Hall thruster's cathode flow fraction (the ratio of flow to the cathode to the flow through the anode) can have some impact on the overall thruster performance.[12–20] Similarly, we have established in our previous work[20] that how a key parameter of the cathode, the coupling voltage, is susceptible to facility effects. These two facts inform our hypothesis that the changes in the acceleration zone may somehow be a consequence of how the cathode environment responds to background pressure. As an example of how this might occur, it is possible that a change in cathode coupling voltage will result in a different boundary condition (between the cathode and the thruster plume) for the downstream potential of the acceleration zone. Since electrons propagate upstream from this cathode boundary, such a change could impact the upstream plasma dynamics, thereby potentially altering the acceleration zone structure. Alternatively, as Hargus *et al.* showed in their study of BHT-200, the most important variable driving this facility effect may be changes in the neutral density environment in the near field.[9] The hollow cathode, by virtue of its proximity to the thruster, is a very efficient source of neutrals. In this way, it may also impact the acceleration zone.

With these arguments in mind, the overall goal of our experimental campaign is to determine if we can shift the acceleration zone location by changing the cathode environment in a controlled way. However, isolating the cathode's susceptibility to facility effects, and in particular background pressure, is a particularly difficult challenge. This is partially because the cathode and thruster are intrinsically linked. In practice, it is difficult to raise the background pressure only near the cathode versus only near the thruster discharge to see the disparate effects. Ideally, we would be able to preferentially inject neutral gas into the cathode plume to isolate this cause; however, this is not practical. In the absence of this ability, one possible approach to isolate the pressure dependency of the cathode flow environment is to change the cathode flow rate. To our knowledge, the effect of the cathode flow fraction on the acceleration region has not been studied. The main purpose of this work is to characterize this effect.

To this end, this paper is organized in the following way: First, we provide an overview of the experimental apparatus used to perform this study, followed by a description of the test matrix. Then, we present measurements of the movement of the acceleration zone and inferred quantities as functions of the facility pressure and cathode flow fraction. Finally, we offer concluding statements about the impact of cathode neutrals versus background neutrals on the shift of the acceleration zone.

II. EXPERIMENTAL METHODS

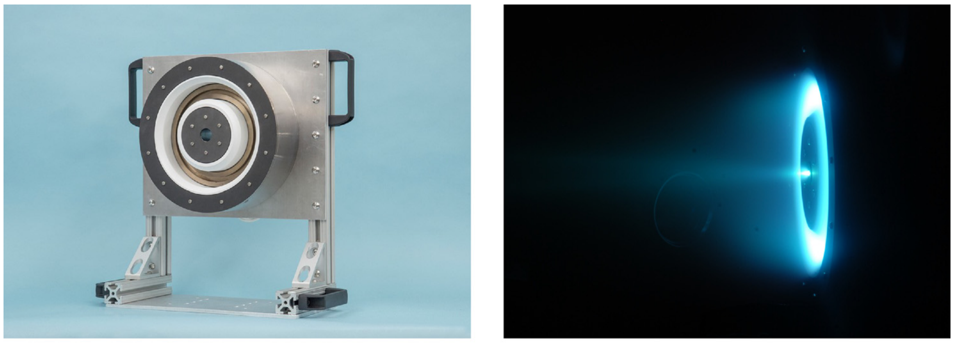
In this section, we overview the experimental equipment used to complete this investigation, including the thruster, facilities, diagnostics, and test matrix.

A. Thruster

Figure 1 shows the H9 Hall thruster used in this investigation. The thruster features magnetic lens topography with magnetic shielding and a centrally mounted lanthanum hexaboride hollow cathode.[21,22] The thruster has a nominal power of 9 kW and a voltage range of 300 to 800 V. The thruster was operated in the constant power mode at a discharge voltage of 300 V and a discharge power of 4.5 kW. In this context, in the constant power mode, we adjusted the thruster flow rate to maintain power as we varied the facility background pressure. Generally, as we increased the facility pressure during our investigation, the discharge current of the thruster would increase due to neutral ingestion. To maintain constant power through the thruster during our pressure studies, we therefore needed to reduce the flow to the thruster. Additionally, the thruster was in the cathode-tied configuration during all testing where the thruster body was at the same potential as the cathode.

B. Facility

The testing was done in the University of Michigan's Large Vacuum Test Facility (LVTF), a 6 meter diameter and 9 meter long vacuum chamber. During this investigation, the H9 Hall thruster used a commercially available 60-kW discharge power supply and four power supplies for the cathode keeper, cathode heater, and electromagnets. Three commercially available flow controllers were used to supply research grade xenon to the anode, cathode, and downstream injection location. In order to increase the facility pressure during operation, xenon gas was flowed into the chamber approximately one meter downstream



(a) (b)

FIG. 1. The H9 Hall thruster immediately after manufacturing (a) and firing at a 300 V discharge voltage and 4.5 kW discharge power (b).

and one meter radially away from the thruster. The flow was directed away from the thruster to ensure that neutrals were not preferentially directed towards the thruster.[23] The pressure in the chamber was monitored using a Stabil Series 370 Ion Gauge calibrated on xenon. It was placed axially in line with the thruster exit plane, approximately one meter from the thruster.[24] The entrance of the gauge was covered with a grounded copper mesh to prevent ambient plasma from entering the gauge. There was a second mesh at the entrance to the snorkel in line with the design described by Dankanich.[24] The base pressure of the chamber during this experiment was 5×10^{-7} Torr-Xe. Prior to any measurements being taken, the thruster was out-gassed for approximately 4 h to ensure nominal operation. Measurements were only taken once the thruster had reached the thermal steady state (less than 5 °C change per hour).

C. Laser-induced fluorescence

We characterized the ion velocities in the thruster's acceleration region using a standard, non-resonant laser-induced fluorescence (LIF) diagnostic commonly used for Hall thruster studies.[7,9] In this setup, we employed a tunable diode laser and a tapered amplifier to produce a laser beam with an output linewidth of less than 200 kHz targeted at the $5d^4_{7/2} \rightarrow 6p^3_{5/2}$ metastable transition of xenon ions. We generated measurements of the ion velocity distribution function (IVDF) by injecting this laser into the thruster plasma, sweeping it over a range of wavelengths (834.9 to 835.02 nm), and monitoring the intensity of the fluoresced signal induced by the laser from a fixed point in the plasma with collection optics.

In practice, the beam was sampled with a photodiode to measure the intensity and then sent through a chopper to mechanically modulate the signal before being collimated and sent into the chamber. Inside the chamber (Fig. 2), there were two optical elements: the axial injection optics and the collection optics. The intersection of these two elements represents the localized interrogation volume which was 1 mm^3. Both the injection and collection optics were stationary throughout the experiment. The thruster, on the other hand, was placed on two-dimensional motion stages and translated in order to generate spatially resolved maps of the acceleration region. These spatial sweeps were taken from the exit plane (0 mm) to 15 mm downstream of the exit plane in 1 mm increments along the thruster channel centerline. The collection optics, which were placed 60° off axis to protect them from the plasma plume and allow unlimited access into the thruster, were used to collect the light fluoresced by the ions excited by the laser. This light was then sent out of the chamber and into a monochromator tuned to 541.91 nm. After the monochromator, a photomultiplier tube converted the optical signal to an electrical current, and a trans-impedance amplifier converted the signal to a voltage that was measured by a lock-in amplifier. By measuring the intensity of this as a function of the wavelength and employing a Doppler conversion, we were able to generate spatially resolved measurements of the axial component of the IVDF in the thruster plume.

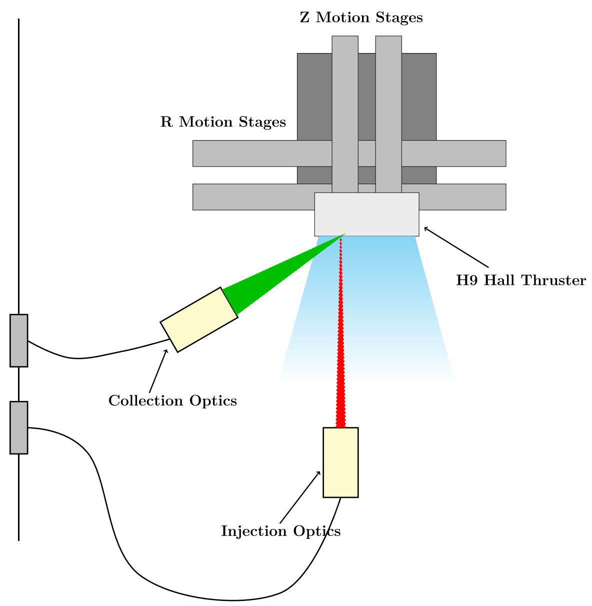


FIG. 2. Internal setup for laser-induced fluorescence measurements.

The IVDF measurements were subject to sources of shifts and broadening such as Zeeman splitting and hyperfine structure.[9] However, most of these effects were generally small compared to the Doppler broadening of interest. Additionally, these effects were symmetric about the stationary transition wavelength and therefore should not impact taking the first moment to infer average ion velocity (see Sec. III A).[11] Therefore, no corrections for these effects were made. Finally, we confirmed that we were not operating near saturation by checking the linearity of the fluorescence signal versus laser power.

D. Test matrix

For this study, we operated the thruster with the test matrix detailed below. The base condition was defined as the condition with a nominal cathode flow fraction and no injection downstream to increase the background pressure. The pressure during this case was 7.1×10^{-6} Torr-Xe. For the background pressure study, we increased the pressure in steps of approximately 5×10^{-6} Torr-Xe until the chamber pressure was 3×10^{-5} Torr-Xe. These test points are henceforth referred to as the "pressure sensitivity" measurements. For the "cathode flow fraction sensitivity" measurements, the cathode was operated at cathode flow fractions of 7%, 10%, 12.5%, and 15%. The nominal cathode flow rate was 1.1 mg/s (7%). The maximum cathode flow rate was 2.4 mg/s. During the cathode flow fraction test, no power corrections were needed to maintain a constant discharge current as there was no increase in flow to the anode, and the background pressure did not change outside the uncertainty of the pressure measurement.

III. RESULTS

In this section, we present our analysis methods for the laser-induced fluorescence data and the results for these measurements.

A. Laser-induced fluorescence

The raw data collected from the laser induced fluorescence system yield an intensity versus wavelength plot. Here, the intensity is proportional to the number of photons emitted, i.e., the number of excitations at a particular velocity. In our analysis of these raw data, we first correct this measured intensity by normalizing the actual laser power intensity for each given wavelength. Next, the wavelength is converted to velocity by the Doppler shift from the nominal transition wavelength. The resulting profile is thus a proxy for the ion velocity distribution function (IVDF). An example of the resultant plot for the thruster operating at 7% cathode flow fraction and base background pressure can be seen in Fig. 3. This trace is taken 2 mm downstream of the exit plane. Here, we see that the peak is between 5 and 10 km/s. This would suggest that this location is midway through the acceleration region, as the ions have already accumulated kinetic energy but have not reached the velocity expected with a 300 V potential drop (approximately 21 km/s).

Figure 4 shows the color map of normalized intensity versus velocity at each axial location for the base condition. Here, we can see that the most probable ion velocities (proportional to intensity on the color map) start at low values upstream and then accelerate to higher speeds. The so-called "acceleration zone" is this region where acceleration occurs (the region where this transition occurs). The distribution at certain locations appears to be very wide. This is a known effect that has been attributed to plasma oscillations in this region, the overlap between ionization and acceleration regions, or potential heating of the distribution.[7,9] While not reported here, the oscillations for the base case are known to be approximately 33% of the discharge current.[21]

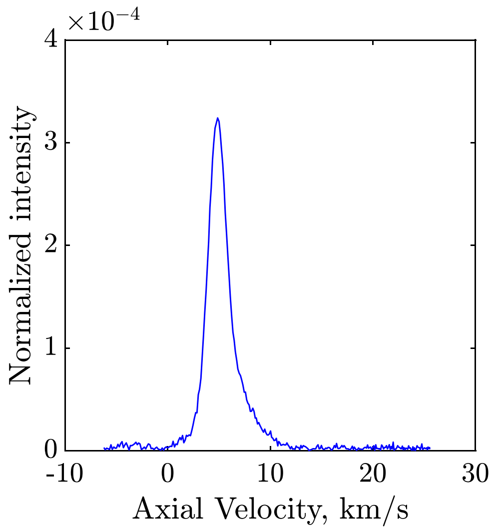


FIG. 3. Example laser-induced fluorescence measurement showing normalized intensity versus axial velocity. This measurement is from 2 mm downstream of the exit plane at the base condition (7% CFF, lowest background pressure).

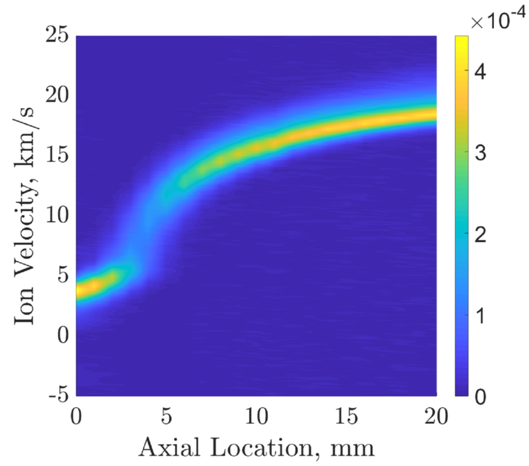


FIG. 4. Color map of the intensity at each velocity point versus axial location for the base condition. The figure shows the main acceleration region starting at approximately 1 mm and ending around 12 mm downstream of the thruster exit plane.

In order to quantify the location of the acceleration region, we first convert each spatial location of the IVDF to an average ion speed

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

where u is the velocity, $f(u)$ is the normalized distribution function (probability versus velocity), and u_1 and u_2 are the limits of velocity space during this investigation (correlated with minimum and maximum wavelengths sampled). We interpret the mean in the ion velocity to be the drift velocity of an ion fluid. Therefore, in order to quantify the uncertainty in the calculated mean velocity, we implemented bootstrapping re-sampling statistics. Each IVDF was re-sampled 1000 times, and the mean velocity was re-calculated. We found the standard error to be approximately the size of the marker in Fig. 5. We repeat this analysis at every axial point to plot the average ion speed as a function of spatial location downstream of the thruster exit plane for each test condition.

Figure 5 shows the LIF results of the pressure sensitivity and cathode flow fraction studies. As expected, the acceleration region shifts inward as the facility pressure increases. This result has been documented on other Hall thrusters[25] and magnetically shielded thrusters with internally mounted cathodes (the same configuration as the H9).[11] Similarly, the results of the cathode flow fraction study show that as the cathode flow fraction is increased, the acceleration region of the thruster shifts inward. This result indicates that cathode changes can directly impact the location of the acceleration region of the thruster. This is, to our knowledge, the first documented shift in the acceleration region location with varying cathode flow fractions.

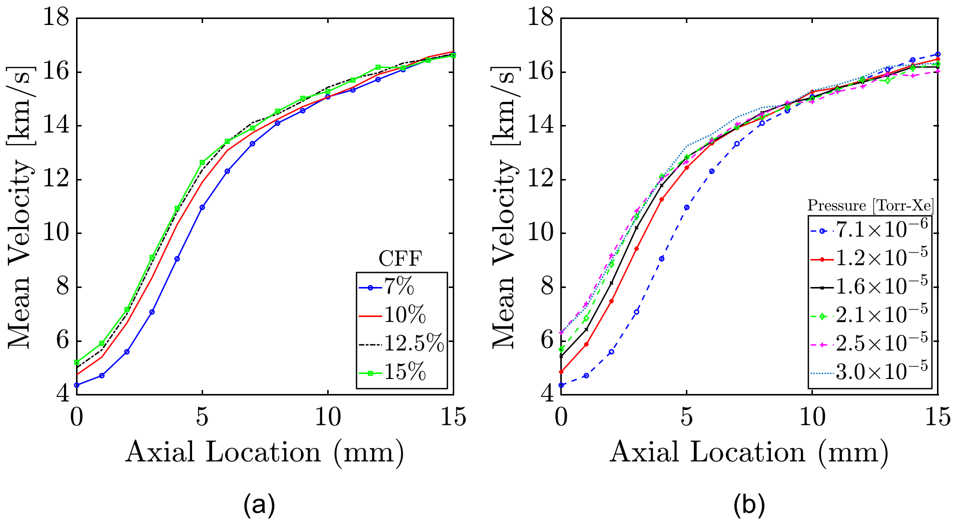


FIG. 5. Mean velocity versus position for the pressure sensitivity study (a) and the cathode flow fraction study (b).

We can quantify these qualitative trends by identifying the location acceleration region with the location of the peak electric field in the discharge. To this end, we first fit a spline to the position versus mean velocity profile. We then take the derivative with respect to the position of this spline to infer the electric field at each point according to the following equation:

$$E(x) = \frac{m_e}{q} u(x) \frac{du}{dx}, \tag{2}$$

where $E(x)$ is the electric field at a given location x, m_e is the mass of an electron, q is the elementary charge, and $\frac{du}{dx}$ is the spatial derivative of velocity. Finally, we find the point of comparison between each condition by locating the peak electric field.

The results from this calculation can be seen in Fig. 6 where the error bars reflect the uncertainty in the location of the LIF measurements, i.e., ± 0.5 mm. Figure 6(a) shows that from the base case to the highest pressure, the acceleration region shifts axially inward 1.6 ± 0.5 mm. Figure 6(b) indicates that the magnitude of the shift with the cathode flow fraction is 0.9 ± 0.5 mm. In both cases, there appears to be a non-linear response to neutral density in that continuing to increase either the cathode flow fraction or the pressure yields smaller and smaller shifts. That is to say, changing the cathode flow fraction from 10% to 12.5% does not yield the same shift as changing the cathode flow fraction from 12.5% to 15%. The same is also true for the pressure study.

The results show that for both the cathode flow fraction and facility pressure, the acceleration region moves axially upstream as these parameters increase. The shift is greater with the pressure changes (30%) but generally follows the same trend. We thus can conclude that qualitatively changing the cathode flow fraction has a similar effect as altering the background pressure. This naturally raises the question of why this is the case. Is it because of something happening localized to the cathode that is changing the cathode dynamics? Or, is it that by

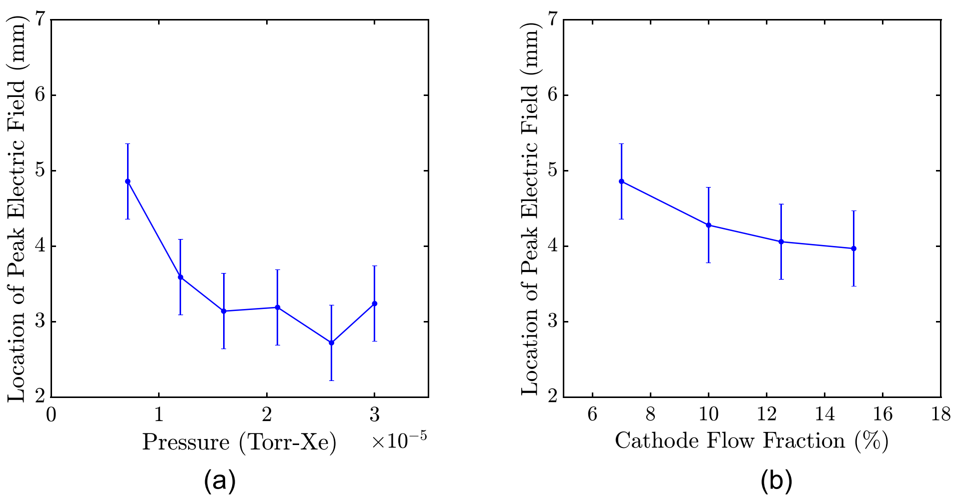


FIG. 6. Location of the peak axial electric field versus background pressure (a) and cathode flow fraction (b).

virtue of the cathode being closer to the thruster, it has the ability to change the neutral density environment near the acceleration region in the same way as changing the background pressure does? We discuss this in the context of both the coupling voltage and neutral density in Sec. IV.

IV. DISCUSSION

To date, there is not a known explanation for the movement of the acceleration region with both varying background densities and cathode flow fractions. We posit here two potential, correlational explanations informed by our results: changing the cathode flow fraction/facility pressure changes the boundary condition for the electric field which shifts the acceleration region (previously theorized to impact cathode coupling[20]) or the changing cathode flow fraction/facility pressure alters the neutral density environments in a critical location in a similar manner. First, we look at the plasma potential structure in the plume.

Figure 7 shows the plasma potential as inferred from our measurements of the ion velocity

$$V_{pot} = V_D - \frac{1}{2} m u_{mean}^2, \tag{3}$$

where V_D is the discharge voltage, m is the mass of a xenon atom, and u_{mean} is the mean velocity of the IVDF. We see that for both conditions, the plasma potential still decreases as a function of the position at the limits of our measurement. However, it appears that all traces have reached the same plasma potential at this point. This confirms that for all cases, we expect the same ultimate velocity. This result in turn suggests that in all conditions, the ions experience the same accelerating voltage drop. In other words, the magnitude of the potential at the boundary conditions remains the same, while the shifts in the acceleration region occur locally between these unchanging boundary conditions. This is supported by Fig. 7, where we see the changes in the potential 12 mm downstream of the exit plane are less than 2%, i.e., within the uncertainty of most measurements. This is a significant result for dismissing the first of our theories for the role of the cathode in this facility effect. In particular, these results seem to suggest that the coupling voltage between the cathode and the thruster plume does not change significantly with the facility pressure or the cathode flow fraction.

As an alternative, we now look at the neutral density changes to get insights into acceleration region movement. The idea here is that the cathode may have the ability to create a similar neutral environment to results from changing the facility pressure in the acceleration region of the thruster. As a simplified approach to examine this, we consider here the neutral density environments proximal to both the acceleration region and the cathode. We know that increasing the cathode flow and increasing the facility pressure will increase the neutral density profile near the thruster. Therefore, we attempt to characterize where in the thruster plume these densities are of similar order of magnitude. To calculate the change in neutral density due to changing facility pressure, we assume that the neutral density is uniform in the near field of the thruster and proportional to facility pressure. The increase in neutral density due to facility pressure increase, and thus, it is calculated using the ideal gas law with the neutral temperature at room temperature. We note that when changing the facility pressure, we did adjust the anode flow rate to maintain a constant power. However, these changes were less than 3% and resulted in an order of magnitude lower change in neutral density than the effect of changing facility pressure. Therefore, we do not account for this decrease here. To determine the neutral density increase due to cathode neutrals, we assume two-dimensional isotropic expansion of the cathode plume into vacuum.

We show in Fig. 8(a) the results for the change in neutral density from both effects at two different locations: in the acceleration region of the thruster and in the near field of the cathode. These results are expressed in terms of the change in neutral density from the baseline (i.e., by subtracting the nominal case). Figure 8(a) shows that the trends are very similar for both the background pressure and cathode flow fraction in the acceleration region. That is to say that the changes in the cathode flow fraction and the changes in facility pressure yield

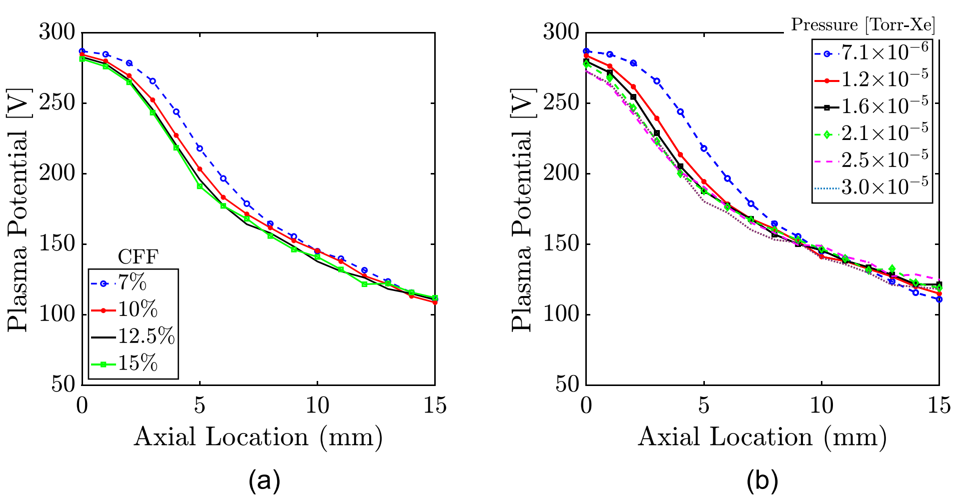


FIG. 7. Plasma potential versus position as inferred from LIF measurements for varying cathode flow fractions (a) and background pressures (b).

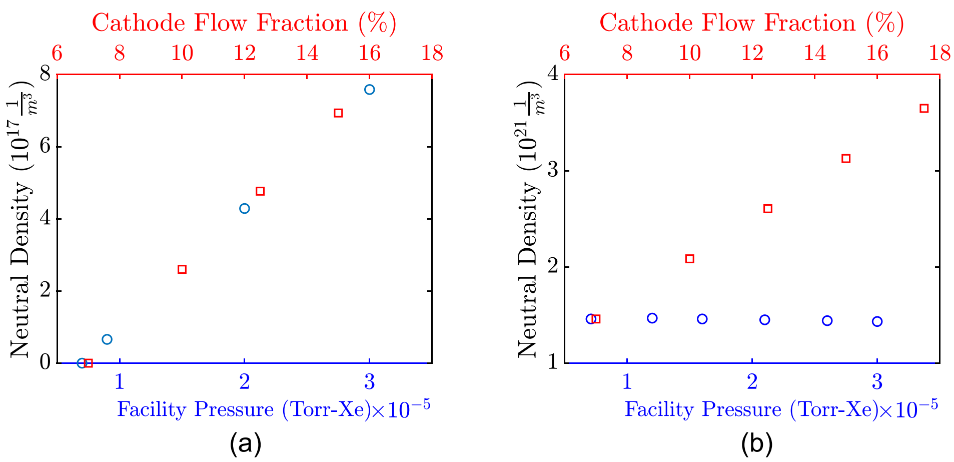


FIG. 8. (a) Expected increase in neutral density near the acceleration region with respect to both the facility pressure (blue) and the cathode flow fraction (red). (b) Expected neutral density 1 cm downstream of the cathode with respect to both the facility pressure (blue) and the cathode flow fraction (red).

comparable changes in the neutral environment in this location. In contrast, on the cathode centerline, just downstream of the cathode, Fig. 8(b) shows that the variation in neutral density due to cathode flow fraction changes is on the order of $10^{21} \times \mathrm{m}^{-3}$. This is four orders of magnitude higher than the background density changes. This suggests that the cathode flow fraction and background pressure change do not yield similar effects on the neutral density in this location.

The fact that the neutral density changes in the acceleration zone, where the plasma is known to shift, are similar for both neutral injection schemes is a significant correlational result. It seems to suggest that the most important parameter driving the acceleration region movements is the neutral density changes close to the acceleration region. A similar finding was made by Hargus *et al.* who noted that it is the neutral density not just the neutral flux in this region that is important for driving facility effects.[9] The reason why the neutral density has this effect is not known, but the correlation may help explain why only incremental changes in the cathode flow fraction are able to produce comparable changes to orders of magnitude changes in the background neutral density environment. Indeed, the cathode is a more efficient source for introducing neutrals to the thruster exit plane than changing the facility pressure, undoubtedly due to its proximity. As a further extension, this finding offers a potential mitigation strategy for facility effects. We may be able to "re-create" many of the facility impacts on thruster behavior simply by varying the flow fraction to the cathode. Alternatively, by running the cathode at a higher flow fraction, we may be able to obtain constant thruster behavior with lowering background pressure. Finally, it is worth noting that most hybrid models[26,27] do not include the cathode or the neutral flow from the cathode in simulations. Instead, they represent the cathode as a point in the domain where the plasma potential is zero. The results here indicate that neutrals emanating from the cathode can impact the acceleration region, therefore suggesting a limitation of these models.

V. CONCLUSIONS

The effect of facility pressure and its correlation with the cathode flow fraction was studied using laser-induced fluorescence measurements of the acceleration region location. The results showed that the acceleration region moves non-linearly inward and qualitatively in the same way for both the increasing background pressure and cathode flow fraction. This is, to our knowledge, the first direct evidence of acceleration region movement with varying cathode flow fractions. In an effort to explain why these two operating parameters have a similar effect on the acceleration region, we have examined two potential theories: the shift is related to the cathode coupling voltage or to changes in the local neutral density environment near the acceleration region. Our results have shown that coupling voltage does not change significantly from case to case, suggesting that a change in the boundary condition does not drive thruster behavior. Our analysis of the neutral density increases due to both conditions, on the other hand, suggests that the density in the acceleration region is the common factor, leading to acceleration region movements. A possible implication of this is that the mechanism governing the shift in the acceleration region depends primarily on simply changing neutral density in the near field. This is a similar result to what was found by Hargus *et al.*[9] Although we have not uncovered the first-principles reason for why neutral density may lead to this change, it does help focus efforts to understand this effect from first principles. From a strictly applied perspective, however, this study indicates that it may be possible to re-create facility effects by changing the cathode flow fraction. Therefore, it would theoretically be feasible to maintain constant thruster behavior by increasing the cathode flow fraction as the facility pressure decreases.

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