

Review of Hall Thruster Neutral Flow Dynamics

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Abstract: A survey of existing research regarding neutral flow dynamics within Hall thrusters is presented. The goal of this research is to determine the microscopic and macroscopic role of neutral flow dynamics in the operation of Hall thrusters, and the details of the relationship with performance, stability, lifetime, and thermal margin. The literature review contained in this paper serves as an introduction to, summary of, and reference for the existing understanding of the role of neutral flow dynamics in Hall thrusters. The significance of the cited work is varied, some of which merely hints at the impact of anodes and neutral flow, while others directly address the subject by performing parametric studies using analytical, computational, or experimental methods. An analytical analysis of neutral flow within the discharge channel is presented, which indicates that increased propellant uniformity and residence time can lead to improved thruster performance. Three-dimensional, continuum-based simulations of the neutral flow within a Hall thruster anode were performed, and the results indicate that axial velocity is strongly dependent on anode temperature. This dependence represents a practical method to increase neutral residence time within the discharge channel, potentially improving propellant utilization.

Nomenclature

A_0	=	cross-sectional area of orifices	[m ²]
B_{av}	=	average magnetic field	[T]
d_o	=	diameter of anode orifice	[m]
E_{av}	=	average electric field	[V/m]
k	=	Boltzmann's constant	[J/K]
L_a	=	length of the acceleration region	[m]
L_{ch}	=	length of the discharge channel	[m]
\dot{m}	=	neutral mass flow rate	[kg/s]
m_e	=	electron mass	[kg]
m_{xe}	=	atomic mass of xenon	[kg]
n_{av}	=	average plasma density	[1/m ³]
n_n	=	neutral number density	[1/m ³]
n_e	=	electron number density	[1/m ³]
P_{CB}	=	continuum-based pressure	[N/m ²]
P_{KB}	=	kinetic-based pressure	[N/m ²]
R	=	gas constant	[J/kg-K]
T	=	neutral gas temperature	[K]
u_e	=	electron velocity	[m/s]
u_n	=	neutral velocity	[m/s]
α	=	neutral temperature accommodation factor	[-]
$\nu_{e,tot}$	=	total electron collision frequency	[Hz]

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ω_e	=	electron cyclotron frequency	[Hz]
Ω_e	=	electron Hall parameter	[-]
Φ	=	plasma potential	[V]
σ_{en}	=	electron-neutral collision cross-section	[m ²]
τ_i	=	ionization time	[s]
τ_{res}	=	neutral residence time	[s]

I. Introduction

CONSIDERABLE effort is being devoted to understanding the role of neutral flow dynamics in the operation of conventional Hall thrusters. In particular, understanding the role of propellant uniformity and residence time in the discharge channel will provide insight into propellant utilization, ionization processes, and electron transport to the anode. This research has potential applications to anode injection schemes and the relationship with thruster efficiency, stability, lifetime, and thermal margin. Anode injection schemes can be altered to maximize propellant utilization by increasing the neutral residence time and azimuthal uniformity in the discharge channel. By optimizing the neutral flow dynamics, the operational envelope of Hall thrusters can potentially be expanded to high specific impulse and high thrust-to-power regimes. At these off-nominal regimes, the importance of propellant utilization and thruster stability is amplified.

Analytical, numerical, and experimental studies are underway at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL) to improve the understanding of neutral flow dynamics in Hall thruster operation. To initiate this effort, a review of existing research was compiled to guide future investigations at PEPL; a summary of the findings is included in this paper. The survey begins with a review of past research concerning neutral flow dynamics that reports changes in the anode injection scheme, discharge channel geometry, and neutral injection temperature. The survey continues with a brief overview of analytical flow predictions and neutral particle diagnostic techniques used for measurements in the discharge channel and plume. The survey concludes with a brief analysis of the consequence of neutral flow non-uniformities and residence time within the discharge channel, with support for the latter provided by a computational study. While the authors have attempted to thoroughly survey the subject of neutral flow dynamics, undoubtedly, we have unintentionally omitted the work of several worthy contributors; for this, we apologize in advance.

II. Past Neutral Flow Dynamics Research

The Hall thruster anode typically serves as the positive electrode and gas distributor, delivering neutrals to the discharge channel through an annular array of small diameter orifices. Based on the spacing and location of these orifices, the axial velocity and azimuthal uniformity of the neutrals can be significantly altered, changing the propellant utilization and electron current to the anode. There is a diverse set of experimental, computational, and analytical research regarding neutral flow dynamics in the operation of Hall thrusters. Studies have modified anode injection schemes, discharge channel geometries, and propellant temperature, concluding that optimizing the neutral flow can positively impact thruster performance, lifetime, and stability.

A. Altering Anode Injection Schemes

Miyasaka *et al.*¹ performed numerical and experimental studies that changed the anode orifice diameter. By increasing the orifice diameter from 2 to 4 mm, the centerline neutral velocity at 4 mm from the anode exit decreased by 20%, while the discharge oscillation frequency and oscillation amplitude decreased by 40 and 70%, respectively. The authors of Ref. 1 concluded that the lower discharge oscillation frequency and amplitude recorded with the 4-mm-diameter orifices were attributed to the increased neutral velocity.

The experimental work of Kim *et al.*² investigated several anode designs and found a traceable effect with thruster performance and lifetime. The study was performed with the PPS-1350 Hall thruster, which was outfitted with several variations of a supplementary cylindrical anode and a reverse-injection anode as shown in Fig. 1, reproduced from Ref. 2. The cylindrical anode was separately operated at the inner, outer, and combined inner and outer radius of the channel. The cylindrical anode was also operated as the primary positive electrode so that the nominal portion of the anode could be operated as a gas distributor only. Most of the anode configurations in Ref. 2 produced thruster efficiencies within $\pm 2\%$ (absolute) of the nominal configuration efficiency of 56%. Several configurations reduced the efficiency below 51%, all of which occurred when the nominal portion of the anode was operated as a gas distributor only, while the supplementary anode was operated as the positive electrode. Although the efficiency was mostly independent of the anode configuration, the plume divergence was more sensitive,

displaying deviations from the nominal configuration of $+8/-0^\circ$. Typically, higher plume divergence resulted in more erosion of the channel outer diameter, with a maximum variation of approximately ± 1 mm from the nominal configuration. The authors in Ref. 2 did not comment on the changes in neutral flow dynamics; however, each anode design iteration likely changed the downstream neutral flow distribution. In particular, the reversed neutral injection configuration likely had a significant impact on neutral flow distribution in the channel, and the configuration likely resulted in an elevated neutral temperature due to increased collisions with the ceramic walls, which tend to be several hundred degrees warmer than the anode surface.

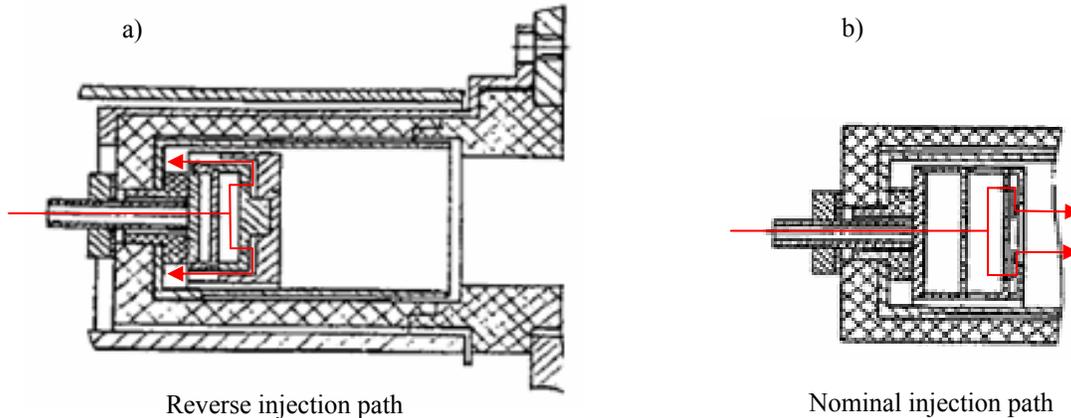


Figure 1. Anode injection schemes used for the experiments in Ref. 2. a) reverse injection, b) nominal anode shown with supplementary inner and outer radii cylindrical anodes.

The work of Vial *et al.*³ indicated that modifying the anode injection scheme can reduce plume divergence angle and increase propellant utilization and lifetime. The study changed the radial position of the anode injection holes from centerline to the inner and outer radii as shown in Fig. 2, reproduced from Ref. 3. Experimental measurements of thrust indicated very little change due to injection location; however, plume divergence was lower for the inner and outer radii injections. The neutral number density was shown to be elevated near the outer radius of the thruster for both off-nominal configurations. The asymmetric neutral number density causes the plasma density to be radially non-uniform, resulting in a more focused electric field. Optical measurements also indicated that ion recombination at the wall was reduced for the off-nominal configurations, which could result in a reduction in erosion rate (i.e., longer lifetime).

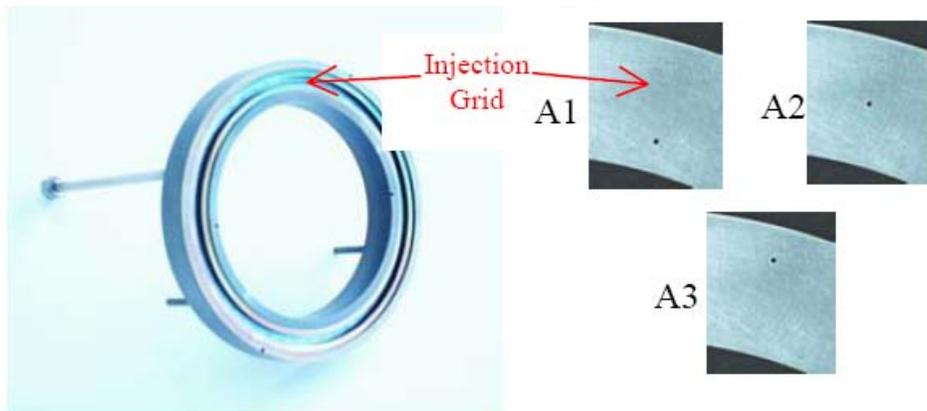


Figure 2. Injection schemes used in Ref. 3, A1) inner radius, A2 centerline (nominal), and A3) outer radius.

The computational work of Garrigues *et al.*⁴ indicated that controlling anode injection schemes can influence thruster lifetime and efficiency. Simulations were performed with a 2-D hybrid model, and a fraction of the anode flow was injected at several axial locations near the interface between the ionization and acceleration zones. A schematic of the experiment is shown in Fig. 3, reproduced from Ref. 4. The total mass flow rate into the discharge

channel remained constant, and the fraction of the total flow injected near the ionization region varied. The thruster efficiency and erosion rate at the discharge channel exit plane were decreased by 1-10% (absolute) and 10-100%, respectively, depending on the axial location of the secondary neutral injection. The reduction in erosion was attributed to a flattened plasma density and a more focused electric field that reduced the number of ions that reached the wall. The efficiency drop was attributed to incomplete ionization of the injected neutrals at the downstream location. The incomplete ionization occurs due to the decreased residence time within the discharge channel, dictated by the effective reduction in channel length. Furthermore, the neutrals injected near the ionization region will likely have an elevated thermal velocity since they are significantly heated by the hot channel walls prior to reaching the discharge channel. This further reduces the residence time in the channel and probability of ionization. The erosion rate and thruster efficiency were sensitive to the downstream location of the neutral injection, with minimum erosion and a peak in efficiency occurring for neutral injection at 80% of the channel length. The results of these experiments indicate that peaked neutral number density near the ionization region likely improves the ionization efficiency. The results also suggest that elevated neutral density near the channel walls reduces erosion, and extends lifetime.

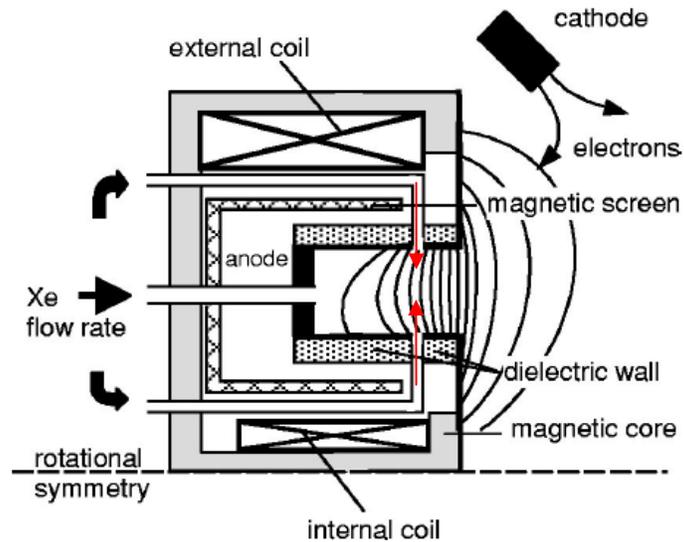


Figure 3. Injection scheme used in Ref. 4. Additional neutral flow was radially injected near the channel exit, shown by red arrows.

B. Altering Channel Geometry

Raitses *et al.*⁵ performed a parametric investigation of the dependence of propellant utilization on channel geometry. The discharge channel length was varied by moving the anode axially as shown in Fig. 4a, reproduced from Ref. 5. At sub-nominal and nominal mass flow rates, the longer channel length produced higher propellant utilization and efficiency, with diminished impact at higher mass flow rate. This experiment indicated an optimum channel length that was dependent on the anode mass flow rate. The experiments in Ref. 5 also investigated the effect of channel width by altering the discharge channel cross section with a ceramic spacer as shown in Fig. 4b. The spacer reduced the channel cross sectional area near the anode and primary ionization region, which locally increased the neutral number density and the probability of ionization. The spacer then tapered towards the channel exit, allowing the plasma to expand and be accelerated by the electric field. At high flow rates the spacer had a negligible effect. However, the spacer improved propellant utilization at sub-nominal and nominal mass flow rates, while efficiency was essentially unchanged. The results for the ceramic spacer may have been more favorable with improved spacer location, width, and shape. The results of these experiments indicate that peaked neutral number density near the ionization region likely improves propellant utilization.

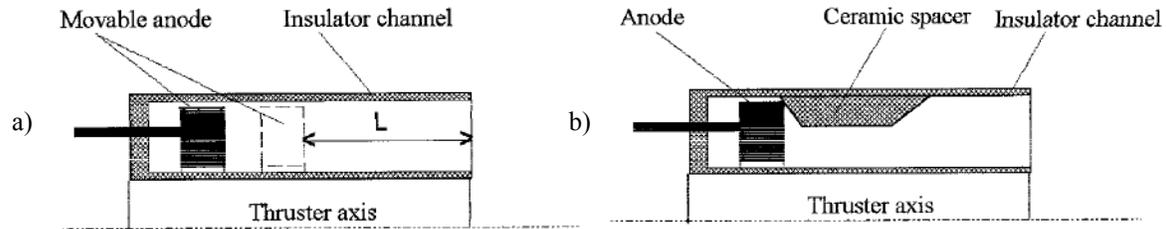


Figure 4. Channel geometry variations used in Ref. 5: a) variable channel length by changing anode location, and b) variable channel cross-section by inserting a ceramic spacer near the anode.

The work of Arhipov *et al.*⁶ indicated that adding a spacer near the channel exit increased ion production, leading to higher thruster efficiency. The resultant channel geometry is shown in Fig. 5, reproduced from Ref. 6. The spacer reduced the channel cross sectional area near the ionization region, which locally increased the neutral number density and the probability of ionization. This study found that moving the plug closer to the anode increased ion density. Langmuir probe measurements confirmed the increased ion production inside the channel; however, a decrease in thruster efficiency was noted, likely due to non-optimal positioning or shape of the plugs. The results from these experiments indicated that peaked neutral number density near the ionization region likely improves the ionization fraction.

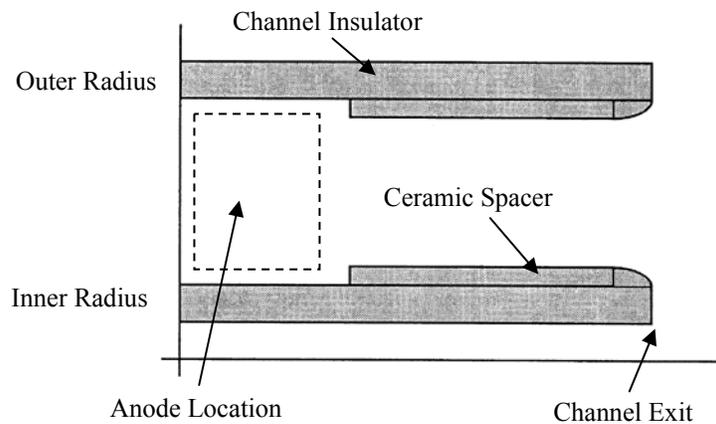


Figure 5. Ceramic spacer used in Ref. 6 to alter the neutral flow within the discharge channel.

Yamamoto *et al.*⁷ changed the discharge channel configuration, showing improvements in thruster efficiency and discharge stability. The thruster was operated with divergent, nominal, and convergent channel exits as shown in Fig. 6, reproduced from Ref. 7. The convergent channel produced higher efficiency due to increased propellant utilization and decreased discharge oscillation amplitude over a wide range of magnetic field strength and discharge voltages. The divergent channel displayed the worst performance and stability. Although not recognized in Ref. 7, the difference in performance is likely attributed to discharge channel width rather than the configuration of the exit plane. By maintaining a constant thruster exit area and conforming the channel to produce the desired shape, the resulting channel widths were 4, 14, and 24 mm for the divergent, nominal, and convergent channels, respectively. Previous work has shown that increased channel width leads to better performance because of the diminishing influence of the walls.⁸ The results of this study may have been more useful if the channel width was held constant and the exit area was altered. Unfortunately, the study did not comment on the implications of channel modifications to thruster lifetime. It is reasonable to assume that the convergent channel will experience increased erosion at the exit plane during the first several hundred hours of operation, and since the channel appears to be thinner (10 mm less than nominal), the overall lifetime may be decreased. Conversely, the divergent channel will likely experience less erosion during the first several hundred hours of operation, and due to the thicker channel wall (10 mm more than nominal), the overall lifetime may be increased.

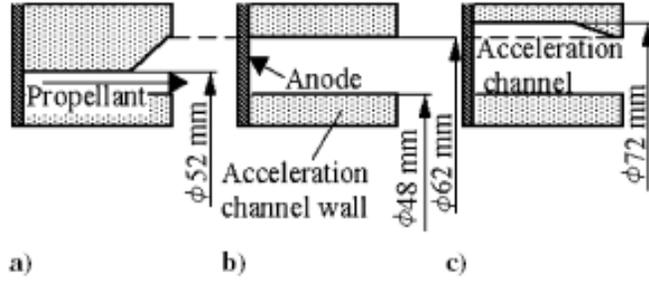


Figure 6. Discharge channel configurations used in Ref. 7 with a magnetic-layer Hall thruster. a) divergent, b) nominal, and c) convergent.

C. Effect of Propellant Temperature

The work of Furukawa *et al.*⁹ explored the effect of pre-heating the neutrals prior to reaching the anode. The results indicated that discharge oscillation amplitude and frequency both decrease with increased neutral temperature. The authors noted that by increasing the neutral thermal velocity the peak ionization zone was pushed downstream, effectively increasing the length of the total ionization zone. However, the increased thermal velocity also reduces the neutral residence time in the discharge channel. The effect of increased propellant temperature on thruster efficiency was not reported, but the authors speculated that efficiency would improve due to the decreased oscillation amplitude and increased ionization zone length.

Kieckhafer *et al.*¹⁰ reported measurements for a bismuth Hall thruster that uses an auxiliary shim anode that is separate from the traditional propellant injecting anode. The shim anode splits the discharge current between the two anodes to actively control the temperature of the propellant injector anode. By modifying the shim current, they were able to decrease the propellant injector anode temperature by approximately 10%, increasing the measured beam current at the thruster centerline. The increase in beam current was speculated to be due to increased propellant utilization, which may be a direct consequence of increased residence time.

The work of Wilbur *et al.*¹¹ indicated improved performance of an ion engine as the neutral temperature was decreased. The neutrals were cooled by a liquid nitrogen shroud that decreased the temperature of the ion engine walls from 500 to 90 K. By reducing the wall temperature, the extracted ion current was increased by several percent at some conditions. This study indicated a clear correlation between the wall temperature and neutral velocity, and the influence on the bulk plasma agreed with predictions. Although performance measurements were not recorded, the increased beam current (at constant input mass flow) indicated that the thruster efficiency increased.

D. Predicting Neutral Flow

Many analytical and numerical studies of the neutral flow within the anode have been presented in the open literature. One such calculation of the neutral flow from the anode inlet to the discharge channel exit is presented in Ref. 12. An accurate prediction of the flow properties within the anode is challenging due to the large changes in pressure and flow regime from fully continuum flow at the anode inlet to nearly rarefied flow at the anode exit. Further, abrupt changes in cross-sectional area accompanied by small diameter flow paths result in non-isentropic losses that must be accounted for by discharge coefficients. To overcome this complication, a semi-iterative process was implemented to adapt continuum- and kinetic-based equations where appropriate. If the flow at a location of interest is considered to be in the continuum regime, then the isentropic approximation is valid¹³

$$P_{CB} = \frac{\dot{m}}{A_o} \sqrt{\frac{R \cdot T}{\gamma}} \left(\frac{2}{\gamma + 1} \right)^{\frac{1+\gamma}{2(1-\gamma)}}. \quad (1)$$

To estimate the pressure at a location considered to be in the kinetic regime, continuity indicates

$$P_{KB} = \frac{\dot{m}}{A} \sqrt{\frac{2 \cdot \pi \cdot k \cdot T}{m_{xe}}}, \quad (2)$$

where A is the cross-sectional area at the location of interest. Flow behavior between the continuum- and kinetic-based regimes is classified as the transitional flow regime. In this regime, it is inappropriate to use the equilibrium approach of the continuum-based equations or the statistical approach of the kinetic-based equations when deriving analytical solutions. We can tacitly assume that the transitional pressure is bounded by the continuum- and kinetic-based calculations (vary by approximately 50%). The calculations performed in Ref. 12 implemented this framework, producing excellent agreement with continuum- and kinetic-based simulations as well as experimental measurements of total pressure downstream of the anode.^{12,14}

E. Anode Sheath

The anode sheath was investigated by Dorf *et al.*,^{15,16} focusing on the effect of a dielectric coating on the anode and its relationship to the anode fall formation. The dielectric coating increased electron current to the anode due to a positive anode fall formation that accelerates electrons to the anode collecting surfaces. The dielectric coating was also suggested to contribute to lower discharge oscillation amplitude, which improved stability. Neutral flow was suggested to play a significant role in preventing pre-ionization within the anode. Pre-ionization has been speculated to increase electron current to the anode and increase the anode temperature, which can alter the neutral flow dynamics in the discharge channel.

F. Neutral Particle Diagnostics

Measuring the properties of neutral particles in partially ionized plasmas is difficult since neutrals are not detectable by electrostatic probes. To solve this problem, scientists have implemented various optical diagnostics or electrostatic filtering of the charged particles to measure neutral properties. A brief summary of these efforts follows.

1. Electrostatic Probe Diagnostics

Experimental measurements of neutrals in the plume were performed by King *et al.*¹⁷ with a neutral particle flux probe. The probe was comprised of several grids to filter ions and electrons and an ion gauge at the rear to measure the neutral density. The probe was able to provide a reasonable measure of the neutral component of the plume, but the results are viewed with some caution since there is no robust method for calibration. Similar to the neutral particle flux probe, Walker *et al.*¹⁸ used an ionization gauge with an inlet that was parallel to the ion flow and had a floating grid to prevent electrons from entering the probe. The probe provided a repeatable neutral component of the plume, but the results must also be viewed with caution due to the absence of a robust calibration.

A robust method to measure the neutral flux inside the discharge channel during cold-flow operation (no plasma) involves inserting a pitot tube into the flow to measure the neutral particle flux with a pressure transducer. Reference¹⁹ contains a wealth of information regarding the use of pitot tubes in high Knudsen number flows, and the report suggests that the probe inlet be chamfered to reduce inlet effects. Using similar techniques, Oghienko *et al.*²⁰ used an axially aligned pressure transducer, with several radially aligned pressure taps recessed into the discharge channel to measure the axial and radial neutral flux. The fidelity of the measurements was not reported, but they were able to discern changes in anode conditions with their experimental setup. deGrys *et al.*²¹ used an axially aligned probe to measure the cold-flow pressure at the anode centerline. The reported probe error was approximately 3%, and a single azimuthal sweep on the anode centerline was used to verify the azimuthal uniformity of a newly fabricated anode. Reid *et al.*¹⁴ measured the neutral flow distribution at a range of azimuthal and radial locations downstream of the anode by using an axially aligned pressure transducer. These measurements displayed a relative error of 1% and the results compared favorably with numerical and analytical predictions.

2. Optical Diagnostics

Laser-induced fluorescence (LIF) is a widely used method of measuring particle properties in the presence of a plasma discharge. Similar to the methodology used for ions, neutral properties are determined by tuning a laser to a particular wavelength of interest and detecting the excited state transition. Bonnet *et al.*²² used LIF to measure the neutral axial velocity within the channel as a function of distance from the anode exit in a SPT50 Hall thruster. The axial velocity at the anode exit plane was approximately 140 m/s, and at 5mm downstream of the discharge channel exit the axial velocity was 470 m/s. Hargus *et al.*²³ was able to measure the neutral axial and radial velocities in the very-near-field plume of a 200-W Hall thruster. The neutral axial and radial velocities on centerline of the channel exit were 300 and 100 m/s, respectively. The results indicated that the neutral density was an order of magnitude larger at the cathode than at the channel centerline. This result is expected due to the weakly ionized plasma that issues from the cathode, which has a higher neutral density than the highly-ionized plasma that issues from the

channel. Although the errors in neutral LIF measurements are relatively small, the spatial resolution tends to suffer due to large data collection time constants. The fidelity of these measurements is also highly dependent on the neutral number density and amount of excitation. Based on these weaknesses, neutral LIF has proven challenging on larger, high-efficiency Hall thrusters that tend to have high propellant utilization (less neutrals in the very-near-field plume).²⁴

Using a similar principle to LIF, Mazouffre *et al.*²⁵ used a method referred to as Fabry-Perot interferometry to measure neutral xenon properties. This study determined that the xenon temperature 7 mm upstream of the channel exit was 900 K, and noted the Zeeman effect at the often used 823.2 nm transition line. Again, long data collection time constants prevent a detailed spatial investigation.

Although fundamentally similar to LIF, electron induced fluorescence (EIF) uses a radically different excitation method achieved with a high-energy electron beam (rather than laser). Vial *et al.*³ used a 10 keV electron beam with a maximum emission of 10 μ A to measure the neutral number density inside the channel of a SPT100 without a plasma discharge. The results were used to validate a simulation, and the comparison indicates that the neutral injection and wall collisions should be modeled as perfectly diffusive.

Cappelli *et al.*²⁶ used a reflection-reabsorption method with a vacuum ultraviolet transition in atomic xenon as a source for absorption. They were able to determine the neutral number density on an axial line downstream of the discharge channel with an error of approximately 50%. The study confirmed the sharp decrease in neutral density when the thruster transitions from glow discharge to jet mode, and quantified the exponential decay of the neutral number density with increased axial distance from the channel exit.

Beverini *et al.*²⁷ used laser-diode spectroscopy to time resolve the neutral density in the plume of a Magneto-Plasma Dynamic thruster. The laser was swept 30 GHz across the transition line at a rate of 100 kHz. This relatively high sampling rate has promise for high-speed time-resolved measurements of neutral density downstream of a Hall thruster that can be correlated to discharge oscillation phenomenon.

Two-photon LIF was implemented by Crofton²⁸ to determine the neutral temperature downstream of an ion engine during hot- and cold-flow operation (thruster on and off, respectively). Measurements taken during cold-flow conditions at several axial locations agreed well with modeled behavior, displaying an exponential falloff with increasing downstream distance. The study also concluded that as beam current increases, the number density of neutrals in the plume reduces, which leads to higher propellant utilization.

III. Discussion

To better understand the relative importance of neutral flow dynamics in the operation of Hall thrusters, the effects of anode injection schemes must be fully understood. Of particular interest is the effect of anode injection schemes on the azimuthal uniformity and residence time of neutrals in the discharge channel; a brief justification for the importance of these effects follows.

A. Azimuthal Uniformity of Neutrals

In the Hall thruster discharge channel, electrons are impeded from reaching the anode by the strong magnetic field. Electron mobility is increased due to collisions with neutrals, and migration towards the anode is achieved through a random walk process. Diffusion across the magnetic field lines can be slowed by decreasing the collision frequency (lower density) or increasing the magnetic field strength (decreasing Larmor radius).

Although the magnetic field is relatively weak near the anode, the electrons remain magnetized. However, their mobility is increased due to the elevated neutral density (more collisions). In the presence of an azimuthal non-uniformity in neutral density, mobility will be locally augmented, increasing the electron current to the anode. This phenomenon was experimentally noted in the work of Hofer²⁹ where a manufacturing error caused a location of elevated neutral density at a single azimuthal location within the discharge channel. This non-uniformity resulted in decreased thruster efficiency, plume symmetry, and stability, indicating that small changes in neutral uniformity can significantly affect thruster operation.

Although the anode injection scheme is directly responsible for the neutral density uniformity near the anode, non-uniformities at the anode exit are expected to be significantly reduced within the first 50% of the channel length due to inter-atomic and wall collisions. Since ionization occurs throughout the discharge channel, near-anode non-uniformities will produce a non-uniform, partially-ionized plasma upstream of the primary ionization region. The electrons in this region are quickly magnetized (low mass, high mobility), and begin their azimuthal ExB drift due to the applied electric and magnetic fields. The remaining ions induce an azimuthal electric field due to the ion density

gradient, causing an induced ExB drift towards the anode for a portion of the electrons. The global effect is an increase in the total electron current to the anode, a direct loss in thrust efficiency.

The work of Baranov *et al.*³⁰ supports the above conjecture through a detailed analytical description of the effect of azimuthal non-uniformities in neutral number density. The analysis of Ref. 30 describes how the plasma density adjusts to minimize the azimuthal electric field to account for a neutral non-uniformity, concluding that the axial electric field becomes skewed near the non-uniformity, and electron current to the anode is increased.

Similar to the work in Ref. 30, Yashnov *et al.*³¹ concluded that the quantity

$$\frac{n_{av} \cdot E_{av} \cdot L_a}{B_{av}}, \quad (3)$$

must be constant in the discharge channel to maintain coherence of the Hall current. This formulation indicates that a local decrease in neutral density requires a lower magnetic field or an increase in the acceleration length or electric field. Since the magnetic field is externally applied (fixed) and the acceleration length is mostly determined by the discharge voltage (fixed), the local electric field must compensate for the increased neutral density. To satisfy Eq. 3, the local peak electric field location moves downstream in an attempt to augment the local plasma density to match the rest of the channel. A graphical representation of this effect is shown in Fig. 7, reproduced from Ref. 31.

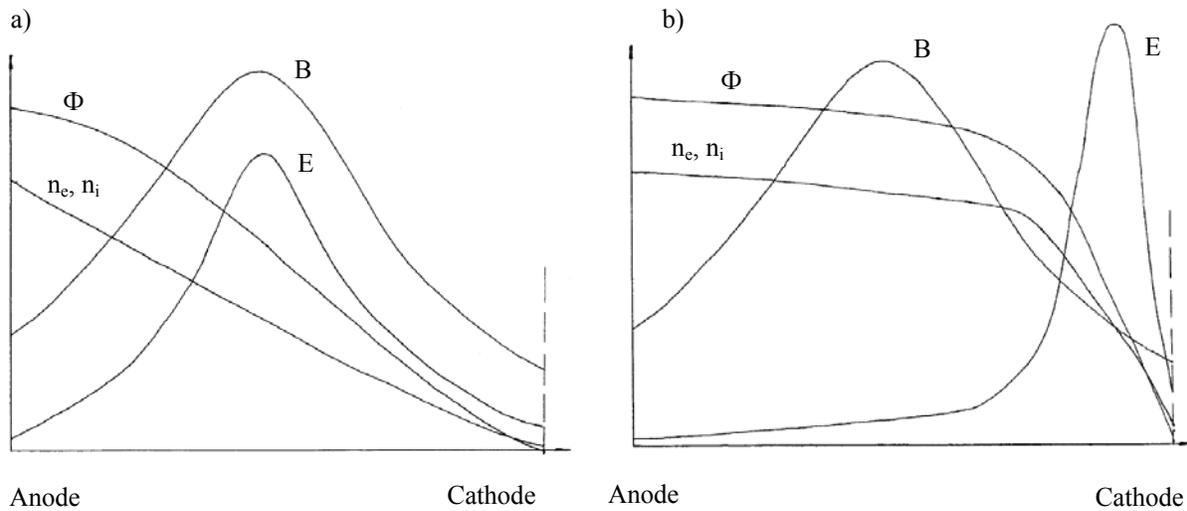


Figure 7. Graphical representation of the magnetic field, plasma potential, electric field, and plasma density for a) typical acceleration zone, and b) altered acceleration zone. Reproduced from Ref. 31.

The assumption of increased electron transport in regions of high neutral density suggests that increased anode mass flow rate will lead to higher electron current (more collisions leads to higher mobility). Contrary to this, thrusters tend to operate more efficiently at higher flow rate where the thruster requires higher magnetic field strength to maintain efficient operation. The correlation between increased magnetic field strength at increased mass flow rate is expected since the electron Hall parameter

$$\Omega_e = \frac{\omega_e}{v_{e,tot}} \approx \frac{1}{50} \frac{e \cdot B T_e^{3/2}}{m_e n_n}, \quad (4)$$

must remain within a particular bandwidth to maintain efficient operation. For a given discharge voltage (electron temperature) and fixed Hall parameter, Eq. 4 indicates that the neutral number density and magnetic field strength must be directly proportional to each other. This analysis puts to rest any concerns about extraordinary electron current at elevated anode mass flow rates. However, the magnetic circuit can typically respond to a relatively small range of mass flow rate increases.

1. Visual Evidence of Neutral Non-uniformities

Figure 8 shows an image of a Hall thruster operating at low voltage and low magnetic field strength that provides visual evidence of azimuthal non-uniformities of neutral density. The bright spots correspond to the neutral injection orifices, where the neutral density is elevated. The increased light intensity is likely caused by augmented electron transport to the anode, which causes increased excitation-induced light emission. The perceived asymmetry about the horizontal axis is due to the camera viewing-angle, which was dictated by the viewport location below thruster centerline. The overall low light level is an artifact of the relatively high shutter speed necessary to view the plasma near the anode ($\sim 1/800$ seconds), and the purple emission is present due to the low discharge voltage and low magnetic field strength.



Figure 8. A photograph of a Hall thruster operating at an off-nominal condition, where the discharge is characterized by increased luminescence at uniform intervals around the circumference.

2. Flow Distributions in the Discharge Channel

Simulated mass flux distributions at the anode exit for the NASA-173M and a 6-kW laboratory model Hall thruster are shown in Fig. 9. The NASA-173M is characterized by uniformly distributed lobes of high mass flux, whereas the 6-kW thruster greatly improves the azimuthal and radial uniformity. The performance of the 6-kW laboratory model Hall thruster exceeds that of the NASA-173M, due to several factors including the improved neutral azimuthal uniformity.

B. Neutral Residence Time

Decreasing the axial velocity of the neutrals increases their residence time within the discharge channel, which increases the likelihood of ionization collisions, potentially increasing propellant utilization. To quantify the effect of neutral velocity, the ionization time (τ_i) is compared with the residence time in the discharge channel (τ_{res}). To maintain a high level of propellant utilization, the inequality

$$\frac{\tau_{res}}{\tau_i} \gg 1, \quad (5)$$

must be satisfied. The mean collision time for an ionizing collision between electrons and neutrals is

$$\tau_i = \frac{1}{n_e \langle \sigma_{en} u_e \rangle}, \quad (6)$$

and the residence time within the discharge channel is

$$\tau_{res} = \frac{L_{ch}}{u_n}. \quad (7)$$

The neutral residence time can be increased with a longer channel, however, this leads to increased wall losses and decreased efficiency. Conversely, the residence time can be increased by decreasing the neutral velocity. The neutral velocity can be controlled by altering the anode injection scheme or by directly cooling the anode to reduce the neutral thermal velocity. Cooling the incoming propellant may have little effect since incoming neutrals accommodate quickly to the anode temperature due to the large number of collisions prior to reaching the anode exit. Directly cooling the anode is more effective since the neutral quickly accommodate to the anode temperature.

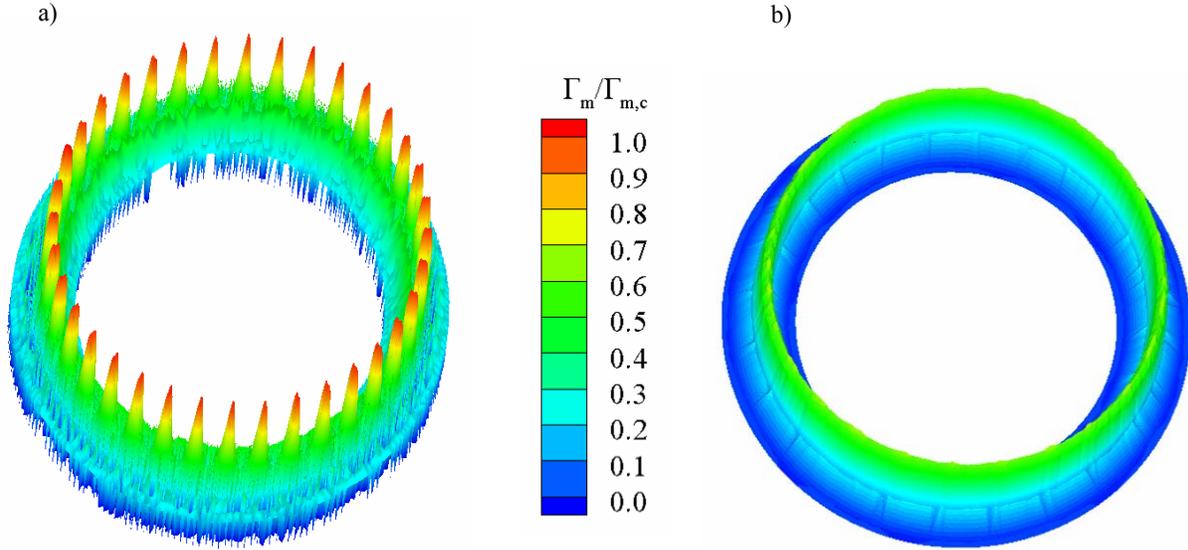


Figure 9. Simulated mass flux at the anode exit for a) the NASA-173M and b) a 6-kW laboratory Hall thruster.

Combining the mean ionization time and neutral residence time, we obtain a criterion for maintaining a high level of propellant utilization

$$\frac{\tau_{res}}{\tau_i} = \frac{L_{ch} n_e \langle \sigma_{en} u_e \rangle}{u_n} \gg 1. \quad (8)$$

Equation 8 indicates that increasing electron velocity (i.e., electron temperature) or reducing neutral velocity (i.e., neutral temperature) will increase propellant utilization, which is similar to the findings of Refs. 2, 32, 33 and 34 that all conclude that maximizing the residence time increases propellant utilization. For a fixed channel geometry, channel material, discharge voltage, and anode mass flow rate, L_{ch} , n_e , σ_{en} , and u_e remain constant, leaving neutral velocity as the only free parameter in Eq. 8. Although magnetic field topology has been shown to play a significant role in the ionization and acceleration process, it is not considered in the present neutral flow based analysis.

C. Numerical Study of Anode Temperature

Building upon the desire to increase neutral residence time in the channel by decreasing axial velocity leads to the logical suggestion of cooling the propellant. Linnell³⁴ attempted to actively cool the Hall thruster anode with a water cooled chiller, but the experiment proved unsuccessful due to an electrical short. To validate the concept of this experiment, the anode flow of the NASA-173M is simulated with the commercially available computational fluid dynamics package Fluent.³⁵ Steady-state, three-dimensional simulations were computed from the anode inlet

through the discharge channel exit. All surfaces are implemented with a low-pressure slip adaptation within Fluent to more accurately model the interaction at the wall for increasing Knudsen number as the flow approaches the discharge channel. The anode body is set to a single temperature that is varied while all remaining variables in the simulation are kept constant. More details on the simulations can be found in Refs. 12 and 14.

To adjust the temperature of neutrals entering the discharge channel, heat can be transferred to or from the neutral particles upstream of the thruster (in flow supply lines) or within the thruster. Due to the large number of neutral collisions with the anode walls prior to reaching the anode exit (continuum flow), the neutral temperature is highly dependent on anode temperature. Hence, heat transfer upstream of the thruster likely has little effect. The independence of neutral velocity on inlet temperature was confirmed with simulations in Fluent that found less than a 1% change in axial velocity over a 100% change in anode inlet temperature.

To reduce the neutral temperature and significantly lower the neutral axial velocity, the anode temperature can be decreased through active cooling. Fluent simulations were performed at anode temperatures from 300 to 1100 K. The results of these simulations are included in Fig. 10 and they indicate that cooling the anode reduces the axial velocity at the anode exit as expected. The centerline value and average value across the anode exit plane are shown, with each displaying a clear square-root dependence on anode temperature. In particular, the velocity dependence agrees well with the Maxwell-Boltzmann distribution

$$u_n = \sqrt{\frac{8 \cdot k \cdot \alpha \cdot T}{\pi \cdot m_{xe}}}, \quad (9)$$

where the temperature is taken as the anode temperature, and α is introduced as the neutral temperature accommodation factor, having a value of one for full accommodation to the anode temperature. The relationship of neutral velocity with anode temperature given by Eq. 9 is shown in Fig. 10 with dashed lines. Eq. 9 closely models the centerline velocity for $\alpha = 1.0$, and the average velocity at the anode exit is modeled by $\alpha = 0.25$. The constant value of α for the centerline velocity and average anode injection velocities presents the possibility to reconstruct the velocity distribution at the anode exit plane based solely upon the anode temperature (assuming a quasi-Gaussian shape).

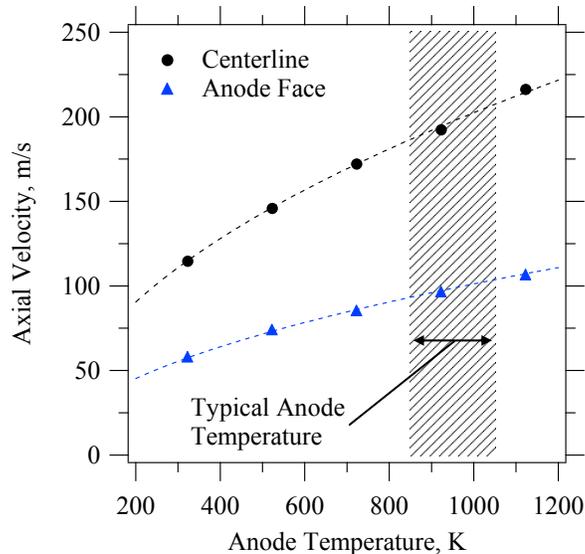


Figure 10. Simulated axial velocity variation with anode temperature at anode centerline and across the anode exit. Square-root dependence of axial velocity on temperature is shown by the dashed lines.

IV. Conclusion

The review of previous research contained in this paper indicates that improvements in propellant utilization, thruster efficiency, stability, and lifetime can be realized by optimizing the anode injection scheme and discharge channel geometry. The optimizations are primarily focused on increasing the azimuthal uniformity and residence

time of neutrals in the discharge channel and increasing the neutral density near the ionization region. By increasing the azimuthal uniformity within the discharge channel, the electron current to the anode may be significantly reduced. Increasing the neutral residence time in the channel and increasing the neutral number density near the ionization region likely improves propellant utilization by increasing the probability of an ionization collision prior to reaching the channel exit.

A practical method to increase the neutral residence time within the discharge channel by actively cooling the anode was investigated by computational means. The results indicate that the neutral temperature is directly proportional to the anode temperature. The predictable dependence of neutral velocity on the anode temperature may allow reconstruction of the neutral velocity distribution at the anode exit based solely on the anode temperature.

Building upon the analytical formulary reviewed in this paper, a more detailed analysis will proceed with the goal of providing quantitative validation of the importance of neutral uniformity and velocity. Numerical simulations will be used to supplement the analytical and experimental work, focusing on the near-anode neutral flow dynamics and the interaction with the bulk plasma. Experimental measurements of cold-flow (no plasma) neutral flow distributions will be performed with heated channel walls. This measurement will provide an accurate initial condition for the plasma simulations, and will provide additional understanding of the influence of wall accommodation and neutral velocity. The microscopic effect of anode injection scheme and neutral flow dynamics will be tracked with measurements of plasma potential and electron temperature within the discharge channel. The macroscopic effect will be tracked with plume measurements of ion current density, ion voltage distribution, and ion energy per charge. Neutral velocity and density will also be measured in the plume using laser-induced fluorescence.²⁴

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