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Neutral Ingestion Compensation for Gridded Ion Thrusters via Model Analysis

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Electric propulsion facility effects can obfuscate performance and lifetime assessment for in-space operation. Neutral gas ingestion from the facility can be compensated by modifying discharge flow conditions. To assess this compensation for dc ion thrusters, this effort uses the DC-ION model to characterize the response of the discharge chamber and beam profile through compensation of the discharge cathode and plenum flows over a range of ingestion factors, λ_i, which is defined as the ratio of the mass flow of neutrals from the environment to the mass flow passing out through the thruster grids. Consistent with experimental observation, particular attention is given to changes to single and double ionization rates near the thruster axis where one often finds a peak in the beam profile. Overall, we find that local ingestion rates are very important and that a local neutral density ratio provides critical insight due to cathode plume ionization behavior. The results show that the most accurate compensation results from proportional changes to both the cathode and plenum flow rates.

I. Nomenclature

Variables

Γ	=	particle flux ($s^{-1}m^{-2}$)
λ_i	=	ingestion factor
$\dot{m}$	=	mass flow rate (kg/s)
$\dot{n}$	=	particle generation rate (s^{-1})
n	=	particle density (m^{-3})
ϕ	=	transparency
V_B	=	Beam potential (V)
A	=	Area (m^2)
P	=	pressure ($Torr$)

Subscripts

c	=	cathode
env	=	from the environment into the discharge chamber
g	=	grids
i	=	ions
in	=	entering the thruster
o	=	neutrals
out	=	exiting the thruster
p	=	propellant
pl	=	plenum
t	=	from the thruster or the discharge chamber into the environment

II. Introduction

Accurately predicting in-space thruster performance during electric propulsion (EP) testing is a critical requirement for EP thruster the development, testing, and characterization [1]. “Facility effects” alter thruster performance and behavior during ground testing, leading to uncertainty as to how the thruster may operate in space.

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These facility effects change the lifetime, efficiency, and general performance of the propulsion system, often in unpredictable ways. Identifying these effects and developing methods to neutralize, minimize, or otherwise account for their impact on propulsion operation is a significant effort in the electric propulsion community.

NASA has funded the Joint AdvaNced PropUlsion InStitute (JANUS) in a 5-year effort towards enabling high-power EP systems and proliferating the use of such systems in space missions [2]. JANUS is specifically focused on the development of predictive engineering models (PEM) that can be used to predict high-power thruster life and performance in space from the results of in-facility testing [3]. As a physics-based effort, understanding facility effects and quantifying their impacts on thruster operation are pivotal to the goals of JANUS.

One critical facility effects is the presence of background gases in ground-based vacuum facilities, which is especially challenging for high-power thrusters with higher propellant throughput [4]. Efforts are ongoing in determining how to compensate for the effects of these background particles within the chamber and their ingestion into or interference with the operation of the propulsion system. Additionally, demands for the next generation of electric propulsion systems exacerbate these concerns. The recent Double Asteroid Redirection Test (DART) Mission demonstrated NASA's Evolutionary Xenon Thrust – Commercial (NEXT-C), a GIT which operates at up to 6.8 kW [5]. The primary life-limiting mechanisms for the NEXT and NEXT-C were determined to be screen grid erosion at lower throttle levels and electron backstreaming due to cell grid erosion at higher throttle levels [6]; both of these phenomena can be significantly affected by changes to ion generation within the discharge chamber and thus are subject to neutral ingestion as a facility effect. Other high-power GITs such as IT-500 and the Nuclear Electric Xenon Ion System (NEXIS) are expected to operate at even higher thrust and thus will likely experience similar issues [7].

Neutral ingestion from the facility leads to increased neutral density in the discharge chamber where ions are generated for extraction through the grids [8]. As such, ingested neutrals can act as additional propellant for the device, increasing efficiency and power artificially [9]. Standards developed recently within the electric propulsion community recommend maximum background pressures at which to operate various devices to minimize this ingestion, with the recommendation for gridded ion thrusters (GITs) stated as approximately 10^{-6} Torr [10], which is particularly difficult to maintain for future high-power EP missions. Even when operating at such a background pressure, it is common practice to reduce propellant flow by an approximation of the ingested gases in an attempt to approximate true vacuum or, alternatively, to test the device at multiple background pressures and regress operational characteristics to an analytical approximation of their vacuum-operation equivalents [11].

As part of the efforts of JANUS to characterize and understand the impact of facility effects on thruster operation, this paper examines the simulated operation of a GIT in vacuum and ingestion conditions to evaluate traditional methods used to compensate for neutral ingestion and to explore new methods. Computational analysis is used to investigate the plasma behavior due to these compensation approaches and to suggest a new approach that better approximates in-space operation by leveraging the use of the mass flow ratio ratio "ingestion factor", λ_i, as describe previously by the authors [12] and revised below.

III. Approach

The NSTAR GIT discharge chamber is simulated using the DC-ION code initially developed by Wirz and updated at several stages [13-15]. This hybrid discharge model includes 2-D, 2.5-D, and 3D models for capturing a range of species behaviors while providing short model run times (typically <1 hour). Many higher thrust GITs include NSTAR in their lineage, and thus NSTAR stands as an appropriate subject for generalized testing and examination [6]. As the state-of-the-art discharge model for GITs, DC-ION forms one of the critical components of the GIT PEM under development by JANUS [3].

To incorporate neutral ingestion, DC-ION was modified to allow for definition of neutral particle density (m^{-3}) and temperature in discrete segments radially along the grid surface. Using one-sided flux models and given neutral transparency for each segment, neutral flux into the chamber is then included in the standard view factor calculation within the discharge chamber model. Ingested neutrals are then incorporated into the standard modeling and behavior. All ingested neutrals are assumed to be expelled propellant; contamination of the discharge environment with non-xenon particles was not investigated but has been shown to have minimal effect in similar thruster designs [16].

Initial results have been obtained by assuming constant neutral density along the exterior (downstream) face of the grids. However, this assumption is not mandatory; more refined neutral presence can be defined to better fit experimental results. Variations in neutral density along the grid have been estimated as increasing up to 68% near the cathode, which is insufficient to significantly alter simulation results [17].

The ingestion factor λ_i is defined as a ratio of the mass flow of neutrals into the discharge from the environment, $\dot{m}_{env}$, over the total mass flow leaving the thruster, $\dot{m}_{out}$.

$$\lambda_i = \frac{\dot{m}_{env}}{\dot{m}_{out}} = \frac{\dot{m}_{env}}{\dot{m}_p + \dot{m}_{env}} \tag{1}$$

To further define the ingestion factor, we consider that the flow rate from the environment into the discharge chamber consists of (primarily) neutrals from the facility or vacuum chamber that pass through the grids, $\dot{m}_{env}$. The mass flow rate leaving the thruster, $\dot{m}_{out}$, consists of neutrals and ions exiting through the grids. Assuming a simple control volume approach and that no other mass exchange is involved, the steady state condition requires that the total mass entering the discharge chamber equal the total mass exiting the discharge chamber:

$$\dot{m}_{in} = \dot{m}_{out} \tag{2}$$

Since all mass leaving the discharge chamber must pass through the grids, we can further equate the mass flow out to an average flux from the thruster as:

$$\dot{m}_{out} = \Gamma_t A_g \tag{3}$$

where A_{grids} is the area of the grids. The total flow of mass into the chamber, $\dot{m}_{in}$, is the sum of propellant flow and ingested mass flow:

$$\dot{m}_{in} = \dot{m}_p + \dot{m}_{env} \tag{4}$$

$$\dot{m}_p = \dot{m}_{pl} + \dot{m}_c \tag{5}$$

Since the ingested mass likewise must pass through the grid, we can define $\dot{m}_i$ as:

$$\dot{m}_{env} = \Gamma_{env} A_g \tag{6}$$

Therefore, the ingestion factor for a thruster at steady state can therefore be defined as:

$$\lambda_i = \frac{\dot{m}_{env}/A_g}{(\dot{m}_p + \dot{m}_{env})/A_g} = \frac{\dot{m}_{env}}{\dot{m}_p + \dot{m}_{env}} \tag{7}$$

The ingestion factor therefore defines either a ratio of mass fluxes to the discharge boundary or the percentage of mass flow from the discharge chamber that originates from ingestion. This ratio ranges from 0 ($\dot{m}_{env}$ = 0) to 1 ($\dot{m}_{env} >> \dot{m}_p$) and represents the expected impact that ingestion will have on thruster operation. While presented here for a GIT, the ingestion factor is likely of significant import to any plasma-based electric propulsion device operating within a non-vacuum environment.

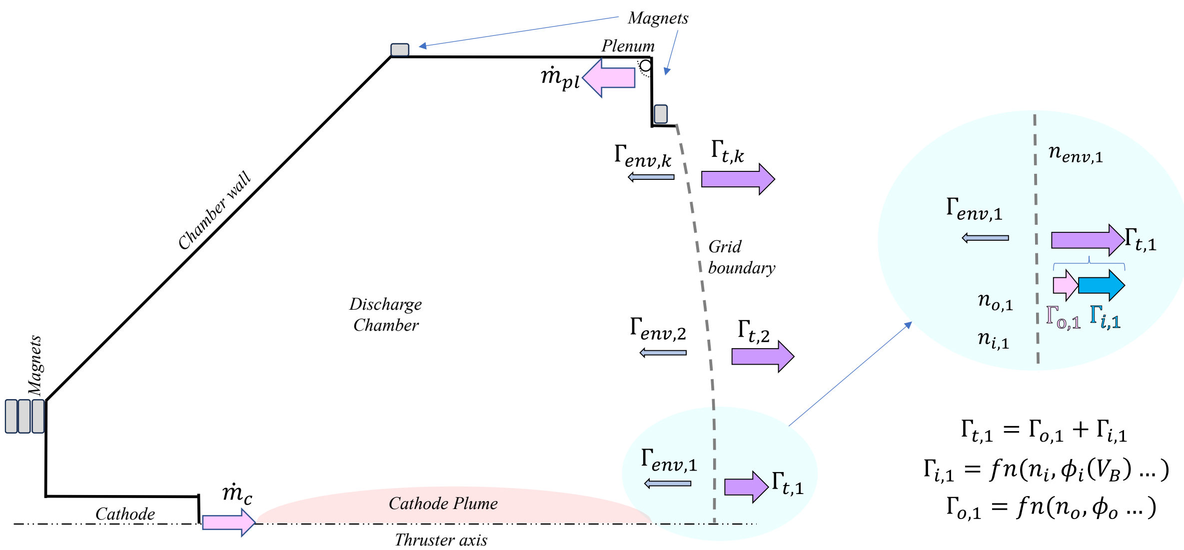

Figure 1 Neutral ingestion along the grid is divided into *k* discrete segments, allowing for future adjustment to downstream neutral density at various locations along the grid. Locally, ingestion is driven by neutral and ion densities on both faces of the grid. Total flux from the thruster is the sum of ion and neutral fluxes.

For simulation, the grid is considered the boundary of the discharge chamber. The grid wall is divided into multiple independent segments; flux through the grid is calculated for each segment individually in both directions (inbound and outbound). Figure 1 shows the discretization of ingestion along the grid into *k* segments. Each segment can be considered as having a local flux ratio determined by local ion (upstream) and neutral (upstream and downstream) densities. For free molecular flow, we consider flux in terms of particles; these values can be trivially converted to mass flow rates for monatomic gases, though care must be taken when working with mixtures or molecules. Total neutral ingestion from the environment is then defined as:

$$\dot{n}_{env} = \sum_{n=1}^{k} \dot{n}_{env,n} = \sum_{n=1}^{k} \Gamma_{env,n} A_n \tag{8}$$

Simulations were conducted using characteristics for the NSTAR thruster operating at TH15 under steady state conditions.

The standard method used to account for ingestion is to treat ingested neutrals as additional propellant and adjust the thruster's propellant feed (through the plenum or anode when applicable) by the amount of ingestion taking place [18]. For sufficiently low ingestion ratios such as those experienced by GITs in most vacuum chambers, this ingested mass flow as a percentage of propellant flow approximates to the ingestion factor λ_i; beyond 5%, the two ratios begin to diverge, with the simple ratio rapidly exceeding the ingestion factor. For an NSTAR thruster operation at TH15, this threshold is approximately $5\text{x}10^{-5}$ Torr, which is consistent with general guidelines for operating the GITs in a facility. Higher powered thrusters with higher propellant flow, however, will generally result in higher vacuum chamber pressures (due to pumping limitations) but can absorb higher ingestion rates as well, while thrusters with lower propellant flow would be susceptible to ingestion at lower facility pressures.

To demonstrate variation between the ingestion factor and traditional linear methods, facility neutral densities corresponding to true vacuum P=0 Torr and P=10^{-4} Torr were conducted. The facility background pressure of P=10^{-4} Torr was chosen specifically to be in excess of the 5% ingestion factor threshold for operation at TH15.

IV. Results

A. Comparison of operation with and without ingestion

The immediate effect of neutral ingestion is the increase in neutral density within the discharge chamber. These neutrals contribute to ionization within the discharge chamber and ion extraction through the grids; in a steady-state analysis, however, this interaction can therefore be observed partially as increased neutral density and increased ion generation and ion density within the chamber.

Figure 2 shows (a) the neutral density profiles between a simulated true vacuum operation and (b) operation at neutral ingestion comparable to $\lambda_i = 8.73\%$ $(\text{i.e.}, P = 10^{-4}\ \text{Torr})$. As shown, uniform ingestion along the grids leads to an increase in neutral density throughout the chamber but varying in intensity. Near the cathode plume along the axis, density increases significantly relative to the vacuum case; density additionally increases along the anode wall at a greater percentage than along the grids. Depletion of neutrals in the cathode plume has been previously documented experimentally [19].

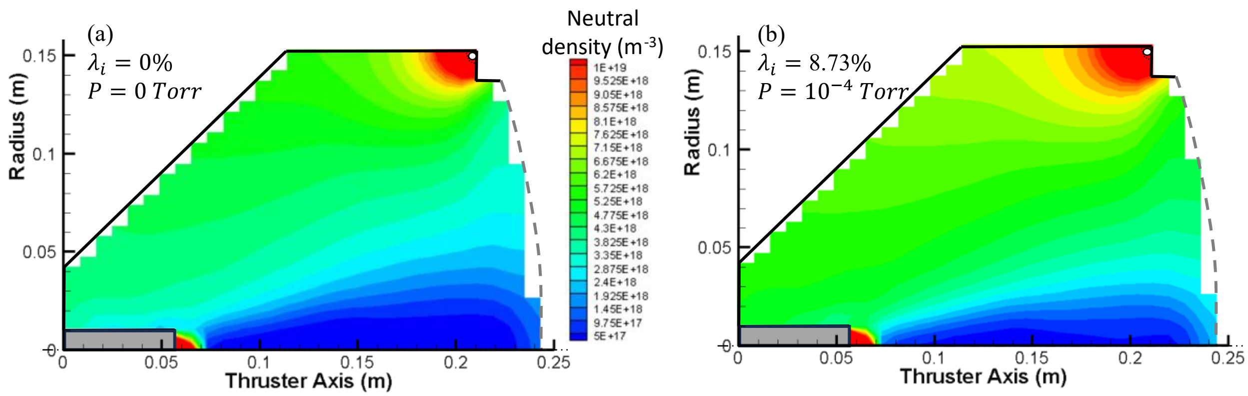

Figure 2 Simulated neutral density (a) within the discharge chamber for the vacuum case with no ingestion and (b) operation with ingestion $\boldsymbol{\lambda_i}$ = 8.73% (P=10^{-4} Torr). Note the increased neutral density both along the axis in the cathode plume and near the plenum.

The variation in density increase is more significant in terms of percentage; Figure 3 shows the neutral density within the discharge chamber when including ingestion at P=10^{-4} Torr relative to the vacuum case. The increased neutral density ranges from just above parity to a factor of 12 at the center of the cathode plume. This is due to the extreme disparity in neutral density in the base vacuum case, where the plenum has regions in excess of 20x the density at the center of the cathode plume. The difference between the base vacuum neutral density variation and the increase from ingestion is due to differences in ionization rates in varying regions of the discharge chamber. The variation in neutral density increase, however, underlies the importance of the ingestion factor: the critical value is not simply a ratio of ingestion to propellant flow but of external flux to the grid relative to internal flux to the grid, the latter of which must include propellant and ingested neutrals.

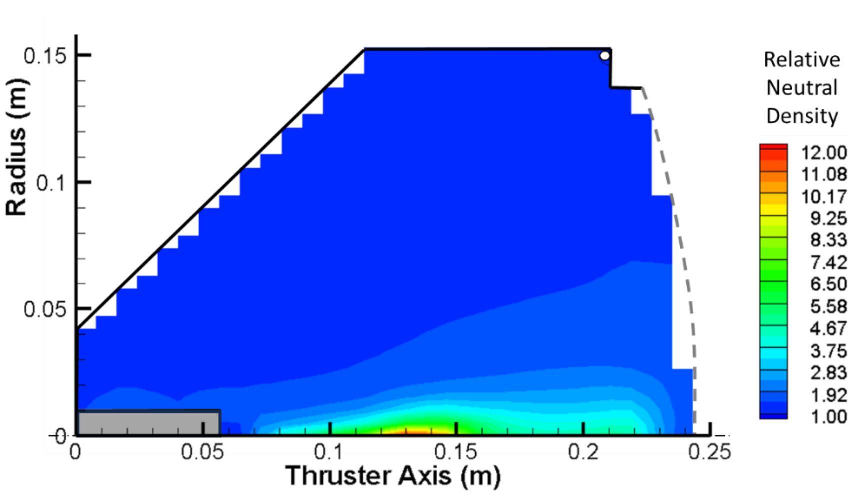

Figure 3 Relative neutral density between the ingestion case $\boldsymbol{\lambda_i}$= 8.73% (P=10^{-4} Torr) and vacuum operation. Neutral density increases throughout the chamber, but the variation is minimal outside the cathode plume.

Ion generation occurs throughout the discharge chamber. The primary region of ion generation is in the cathode plume, where electrons exit the cathode on a largely axial trajectory until they encounter the negative potential from the grids. Figure 4 shows the ion generation rates for (a) the vacuum case and (b) neutral ingestion λ_i = 8.73% (P=10^{-4} Torr) . As shown, ionization increases in the cathode plume region while remaining largely constant in the majority of the discharge chamber. At steady state, the region immediately along the axis becomes highly depleted of neutrals, resulting in increased double ionization events; in (b) the ingested case, the additional neutrals enable a reduction in double ionization and an increase in single ionization. The double ionization ratios for (c) the vacuum case and (d) the ingestion case show the significant decrease in double ionization events in the cathode plume in the ingestion case.

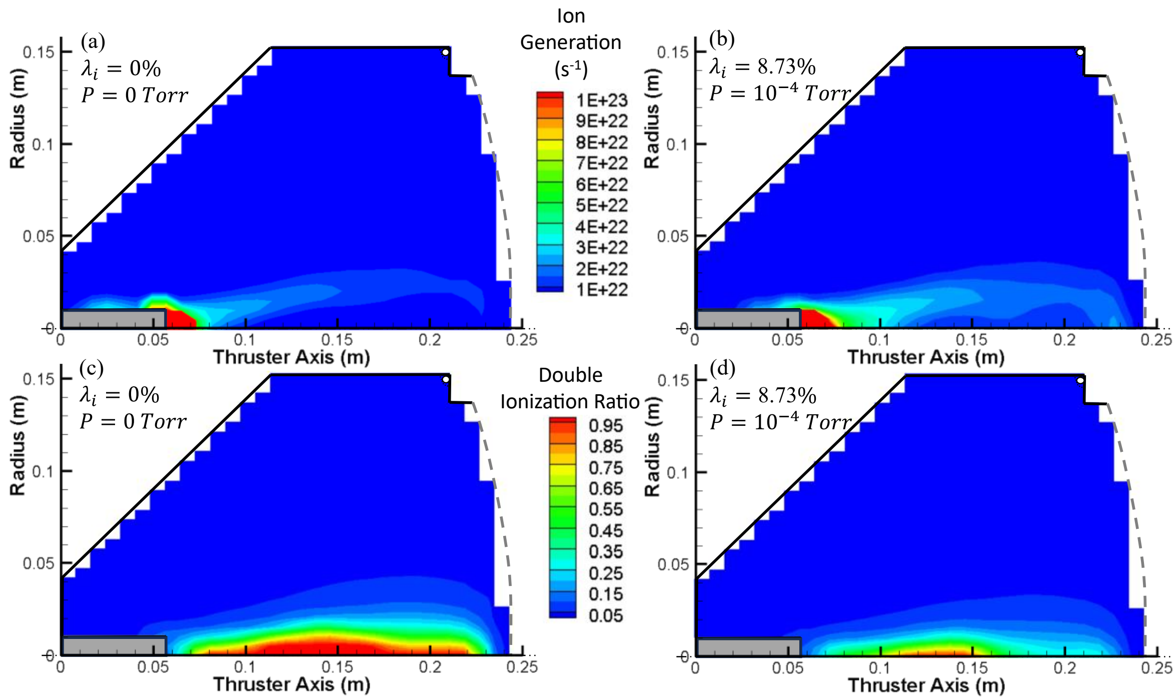

Figure 4 Simulated ionization characteristics within the discharge chamber. Ion generation rates are shown for the (a) vacuum case and (b) the ingestion case $\boldsymbol{\lambda_i}$ = 8.73% (P=10^{-4} Torr). Similarly, double ion ratios are shown for (c) the vacuum case and (d) the ingestion case $\boldsymbol{\lambda_i}$= 8.73% (P=10^{-4} Torr). The increase in ionization rates in (b) also corresponds to a reduction in double ionization in (d) due to the increased neutral density within the cathode plume due to ingestion.

B. Adjustment to compensate for ingestion

As discussed, changes to neutral density and ionization within the discharge chamber are not linear through the chamber even when ingestion is constant along the grid. To compensate for ingestion, we must reduce neutral density within the discharge chamber in such a way as to restore the vacuum-case density and ionization profiles. Our hypothesis is that the predominant feature of a beam profile is the centerline peak, therefore, it may be best to proportionally change the plenum and on-axis cathode flow rates to best compensate for facility neutral ingestion. Thus we will compare two methods as shown in Table 1.

Table 1 Propellant Flow Adjustment Methods

	Plenum Adjustment	**Cathode Adjustment**
Method 1	$\dot{m}_{pl,new} = \dot{m}_{pl} - \left(\dot{m}_{pl} + \dot{m}_c\right) * \lambda_i$ (9)	*No adjustment*
Method 2	$\dot{m}_{pl,new} = \dot{m}_{pl}(1 - \lambda_i)$ (10)	$\dot{m}_{c,new} = \dot{m}_c(1 - \lambda_i)$ (11)

Method 1(Adjusted Plenum) vs. Method 2 (Adjusted Plenum & Cathode)

For TH15, the propellant flow $\dot{m}_p = 1.225\ x\ 10^{19}$ particles/second. The corresponding ingestion rate equivalent to 10^{-4} Torr facility pressure is 1.17 x 10^{18} particles/second. Thus, the ingestion factor is calculated as:

$$\lambda_i = \frac{1.17\ x\ 10^{18}}{1.225\ x\ 10^{19} + 1.17\ x\ 10^{18}} = 8.73\% \tag{11}$$

Using the ingestion factor, we can then compensate for ingestion by reducing propellant flow. For NSTAR and similar thrusters, the standard practice is to solely reduce flow through the plenum for this purpose; this corresponds to Method 1 in Table 1. The new calculated plenum flow is determined using Eq. (9) from Table 1, while the cathode flow is left unmodified.

The (a) ionization and (b) double ionization ratio with ingestion and reduced plenum flow per Method 1 are shown in Figure 5. Note that ionization along the axis remains in excess of the vacuum case (Figure 4a) and the double ionization ratio, while similar, is lower than the vacuum case (Figure 4c). These differences, while small, can lead to significant variation in the beam profile, especially along the central axis.

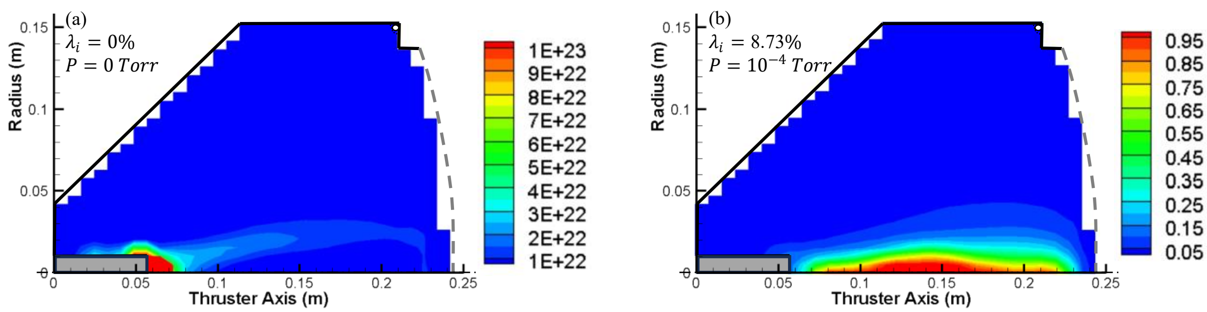

Figure 5 Simulated (a) ion generation rate and (b) double ionization ratio for the ingestion case $\boldsymbol{\lambda_i}$ = 8.73% (P = 10^{-4} Torr) with reduced propellant flow through the plenum.

A comparison of beam current profiles is shown in Figure 6. While the beam profile is largely consistent between the two cases at larger radius values, the variation near the axis is noticeable. The reduction of flow through the plenum does not completely extend to the cathode plume region and thus fails to restore the same ionization behavior in that neutral-depleted region. This leads to the increase in single ionization and the lowering of the axial peak or "nose" of the beam.

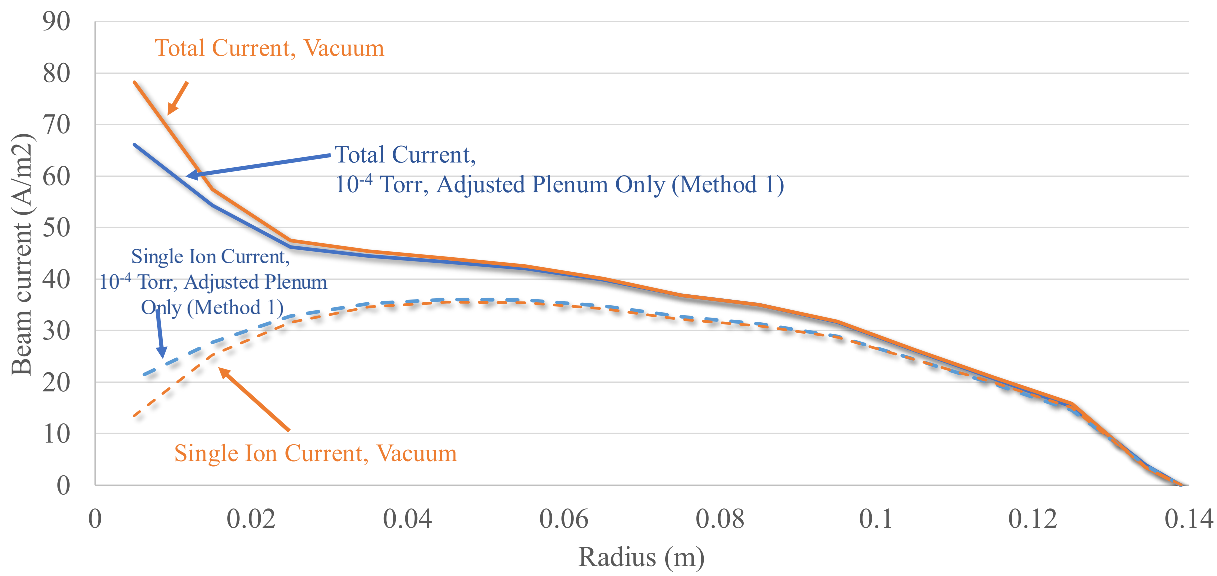

Figure 6 Beam profile comparison between the vacuum case and ingestion case $\boldsymbol{\lambda_i}$= 8.73% (P = 10^{-4} Torr) reducing only the plenum flow using Method 1. Single ion current is shown with the dashed lines, while total current is shown using the solid lines. Reduction through the plenum alone is insufficient to restore the beam profile along the axis.

To better reproduce the vacuum-operation beam profile, it is necessary to deplete neutrals within the cathode plume region. In the final simulation, we used Method 2, where we adjusted both the plenum and cathode propellant flows by λ_i using Eqs. (10) and (11) respectively and observed the results.

Figure 7 shows the beam profiles between the vacuum case and the ingestion case λ_i= 8.73% (P = 10^{-4} Torr) with both plenum and cathode adjusted using Method 2. The profiles overlap very closely along the whole radius, showing that adjustment of the cathode flow is required to reduce the neutral density within the cathode plume.

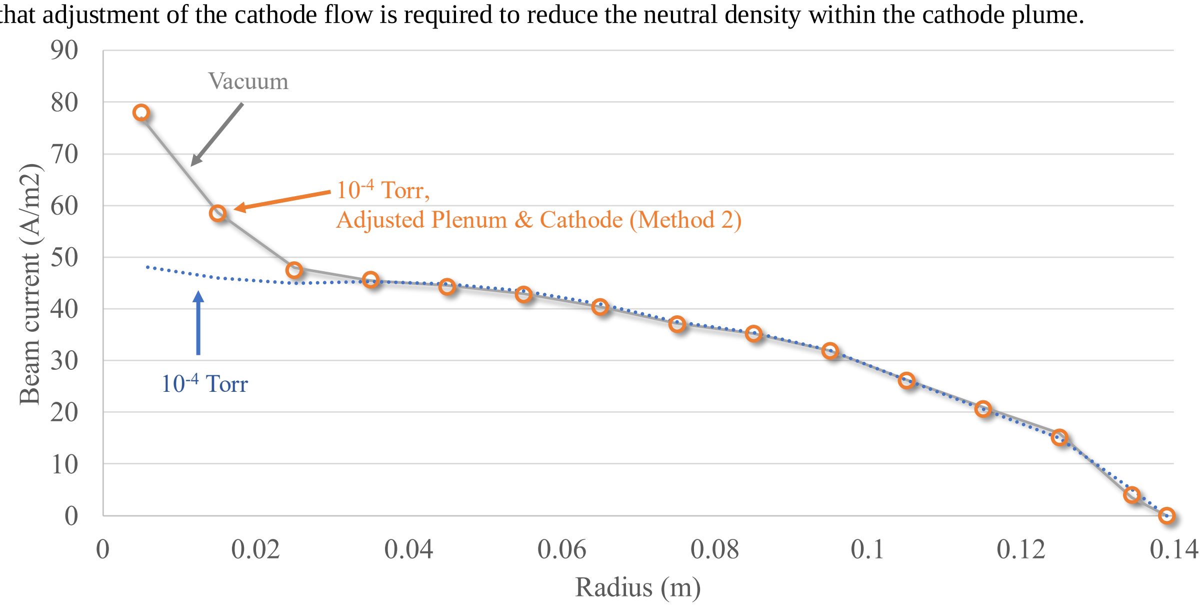

Figure 7 Beam profile comparison between the vacuum case, the ingestion case $\boldsymbol{\lambda_i}$= 8.73% (P=10^{-4} Torr) without adjustment, and the ingestion case $\boldsymbol{\lambda_i}$= 8.73% (P=10^{-4} Torr) with reduction of propellant flow through both plenum and cathode using Method 2. Reducing the cathode propellant flow allows for depletion of neutrals in the cathode plume and restoration of the beam profile to the vacuum case.

Simulations with ingestion factors λ_i=0.95% (P=10^{-5} Torr) and λ_i=4.56% (P=5x10^{-5} Torr) were also conducted, both with and without adjustment to the plenum and cathode propellant flows using Method 2. The resulting beam profiles after adjustment show similar consistency with the vacuum case beam profile (Figure 8).

Simulation with ingestion factor λ_i=32.4% (P=5x10^{-4} Torr) with plenum and cathode adjusted using Method 2 resulted in insufficient depletion of neutral density within the discharge chamber; repeated testing determined the correct adjustment value to be approximately 40%. As such, there may be a limit to the application of Method 2 at sufficiently high ingestion rates (relative to propellant flow). The exact threshold for this limitation needs to be determined.

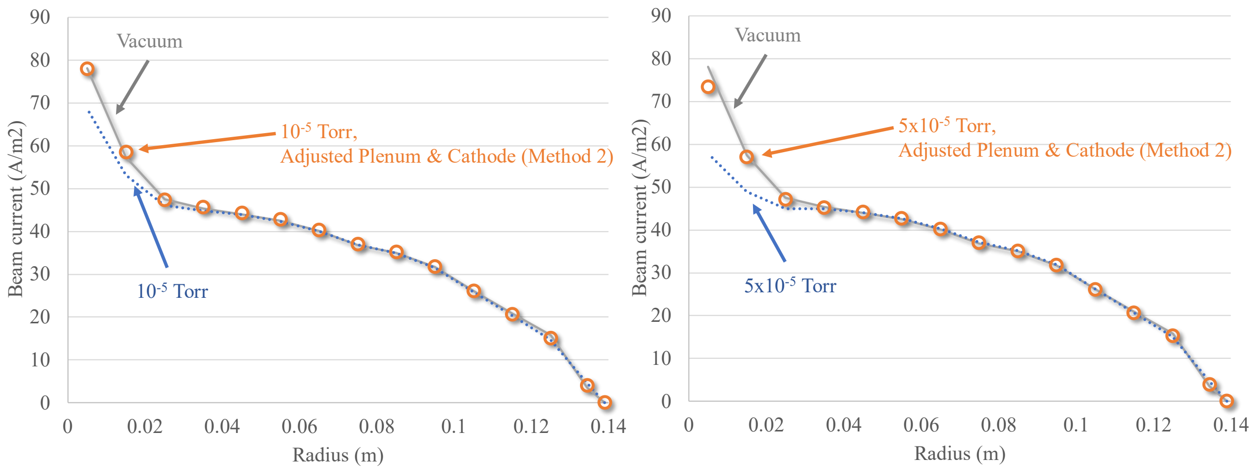

Figure 8 Beam profile comparison between the vacuum case, the ingestion case without adjustment, and the ingestion case with reduction of propellant flow through both plenum and cathode for ingestion cases (left) $\boldsymbol{\lambda_i}$= 0.95% (P = 10^{-5} Torr) and (right) $\boldsymbol{\lambda_i}$= 4.56% (P = 5x10^{-5} Torr) (right) using Method 2.

C. Discussion

The discharge chamber of a GIT is a complex system that, in steady state, balances mass flow in as neutrals and propellant with mass flow out in the form of ions and neutrals. Previous analysis has shown that ingested neutrals cannot simply be treated as additional propellant: reduction of propellant flow by the estimated ingestion has been shown to over-compensate for ingestion rather than restoring vacuum-like operational state [12]. This is seemingly due to the complex relationship between grid ion and neutral transparencies and their effects on particle densities within the discharge chamber.

Understanding these relationships is a critical factor in GIT thruster testing. While standards have been developed to limit the impacts of facility background pressure on thruster operation, no methods exist for completely eliminating these effects [10]. Methods to either adjust thruster operation or translate operational results in order to predict vacuum-like behavior exist, but these are at approximations that neglect the complex effects of ingestion on ion generation. New physics-based methods are needed both for better characterization of current thruster technology and to enable development of high-power thrusters that may force test facilities outside the recommended operational ranges.

Using simulation, Section IV(a) presents the various changes that occur within the discharge chamber due to ingestion. At steady state, an increase in neutral density within the chamber is the most direct effect of ingestion; however, the effects of ingestion in the cathode plume region will be more dependent on the discharge chamber's standard operational state. For NSTAR running at TH15, the cathode plume region is largely depleted of neutrals; in this case, the steady-state result of ingestion is a change in ionization behavior. Electrons leaving the cathode will still work to deplete the region of neutrals, but sufficient ingestion will lead to increased single ion production and reduced double ionization rates. This shift in ionization can have a dramatic effect on the beam current profile, even when ingestion is relatively low compared to the propellant flow.

Instead of simple mass flow into the chamber, then, we rely on particle flux into the discharge region and particle flux out from the discharge region; at steady state, these values must be equal, but the characteristics of the particle flux out from the discharge region will vary depending on the exact relationship between propellant and ingestion. To describe this relationship, the ingestion factor λ_i has been suggested as a ratio of ingested mass flow to total mass flow out of the thruster (Eq. (1)). The ingestion factor describes the relative contribution of ingestion to the discharge.

To account for the facility effect of ingestion, the standard practice is to adjust propellant flow into the discharge chamber. The general method is a simple exchange: propellant is reduced on a 1:1 ratio with ingested neutrals (Method 1). When possible, this reduction is limited to the plenum or main gas feed into the system so as not to interfere with cathode operation.

As shown in Section IV(b), however, Method 1 is insufficient to restore vacuum-like operation. Instead, we demonstrate using a proportional reduction of propellant based on the ingestion factor. In addition, we propose that adjustments to both cathode and plenum propellant flows must be made (Method 2), as re-depletion of the cathode plume region is necessary to restore vacuum-like operation; such re-depletion cannot be achieved by adjustment of the plenum alone. Using Method 2 for three sample ingestion factors equivalent to common facility background pressures restored the discharge conditions and beam current profile to approximations of the vacuum case.

For ingestion factors less than 10%, Method 2 appears to restore vacuum-like operation in simulation with reasonably high reliability. For higher ingestion factors (>30%), adjustment made based on λ_i is insufficient. It is likely there is some other contributing variable that is of low relevance to lower ingestion factors but becomes significant at higher ingestion rates; future work will need to be done to identify this additional contribution. However, such high ingestion factors are unlikely except with very low power thrusters operating in facilities with higher background pressures. The ingestion factor appears to be a useful tool for restoring vacuum-like conditions within the discharge chamber in most medium- or high-power testing.

The current work focuses on using the ingestion factor to modify GIT testing within a facility. In line with the overall JANUS efforts, additional goals include using the ingestion factor to quantify the effects of ingestion of thruster operation and predict what facility conditions are sufficient to minimize the impact of ingestion on thruster operation. Cooperation between experimental, diagnostic, and modeling efforts will be needed to confirm the validity of the ingestion factor and its predictive capability for thruster behavior in various settings; such cooperation is a key facet of the structure of JANUS.

Utilization of the ingestion factor to better approximate vacuum operation of a GIT using Method 2 is as follows:

1. Determine mass flow into the discharge region (or mass flow from the environment into discharge region).
2. Define λ_i as the ratio of mass flow into the discharge region over the flux out of the discharge region (or the mass flow from the environment into the discharge region to the mass flow from environment and propellant into the discharge region).
3. Reduce both cathode and plenum propellant flow rates by the ingestion factor λ_i.

V. Conclusion

Neutral ingestion is a facility effect that can alter gridded ion thruster performance characteristics. In the NSTAR thruster, we show that neutral ingestion significantly increases the quantity of neutrals in the cathode plume, changing ionization behavior along the central axis and modifying the beam current profile and other operational characteristics. As part of the larger JANUS effort, we have defined an ingestion factor, λ_i, as the ratio of ingested neutral flow to total mass flow from the thruster to investigate the impacts of neutral ingestion to the plasma discharge in a gridded ion thruster (GIT) and methods to compensate for that ingestion. By reducing both the plenum and cathode propellant flow values by the ingestion factor λ_i as described in Method 2, a simulated GIT was restored to vacuum-like operational characteristics for NSTAR TH15 throttle condition. Notably, depletion of the neutral density within the cathode plume along the axis required reduction of the cathode propellant flow along with a proportional change to the plenum. In contrast, we found that the conventional method of adjusting only plenum propellant flow to compensate for the ingested neutral "Method 1" proved to not replicate vacuum-like operation.

VI. Future Work

Future efforts on this subject are needed in several areas. First, the simulations here assume constant facility neutral density along the grids; while the variation in neutral density is likely to be of low relative magnitude, it is non-zero and, thus, additional tests with more realistic neutral density profiles are needed. Additionally, all simulations have been run for a single thruster at a single vacuum operation condition (NSTAR, TH15); additional thruster geometries and thrust conditions must be tested. Further, quantification of model uncertainty is necessary both for general use and for incorporation of these results into a predictive engineering model (PEM), as the DC-ION simulation is not exact; such uncertainty quantification is a critical component of JANUS and is planned to be undertaken in separate efforts. The insufficiency of Method 2 at higher ingestion factors must also be examined to determine what if any missing variables should be included. Finally, application of the ingestion factor to other thruster types such as Hall Effect Thrusters (HETs) is reasonable but requires specific analysis due to the significant differences between GITs and HETs.

Acknowledgments

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