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# Technical Notes

## Background Flow Model Validation with a Six-Kilowatt Hall Effect Thruster

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### I. Introduction

THE high specific impulse, thrust efficiency, and thrust density of Hall effect thrusters (HETs) make them an appealing choice for use as primary satellite propulsion systems. However, previous work has shown that these performance attributes are affected by the vacuum facilities in which they are measured [1,2]. Specifically, investigations have shown that an increase in facility pressure results in artificial increases in thrust and efficiency [1]. This performance augmentation has been attributed to the ingestion (and subsequent ionization and acceleration) of facility background neutrals via the random flux of these neutrals across the exit plane of the thruster [1]. Although widely used, this model of ingestion (hereafter referred to as the thermal model) has been shown to underpredict empirical observations by as much as two to 14 times, thus hindering an accurate determination of ingestion and the concomitant changes in HET operating characteristics [3,4].

In addition to these shortcomings, the thermal model assumes that all motion of background neutrals is random. However, modeling of the rarefied background flow inside a HET test facility found that an organized background flow field exists within the test facility with bulk axial velocities of 20–100 m/s [5,6]. Noting that these bulk motions could also enhance HET neutral ingestion, previous work adapted these modeling concepts to generate estimates of HET ingestion due to both bulk and thermal motions of background neutrals [4]. The predictions generated by this new background flow model were compared against empirical data taken with thrusters with both internal and external cathodes (i.e., the P5, H6, and SPT-100) and found to match the empirical observations to within the experimental uncertainty without requiring any empirical inputs such as in situ pressure measurements. These results suggest that the physical mechanisms captured by the background flow model offer a framework to explain the enhanced ingestion rates observed in previous facility effects studies.

In this work, the background flow model is modified to create a specific model for Vacuum Test Facility 2 (VTF-2) at the Georgia Institute of Technology's High-Power Electric Propulsion Laboratory (HPEPL). Direct empirical measurements of the model outputs (i.e., ingestion mass flow rate and neutral number densities near the HET exit plane) are acquired using the H6 HET and compared to the model predictions. These comparisons serve to further validate the model, as well as empirically determine if the physical mechanisms it describes (i.e., the bulk motion of background neutrals) exist and how they impact HET ingestion characteristics.

### II. Experimental Setup

#### A. Vacuum Test Facility

All experiments described in this work were performed in VTF-2 at the HPEPL. A schematic of this facility is shown in Fig. 1, and the facility was described in detail in previous work [7]. The pressure in VTF-2 was monitored using one Agilent Bayard–Alpert (BA) 571 hot-filament ionization gauge controlled by an Agilent XGS-600 gauge controller. This gauge was configured per the guidelines outlined in the best practices guide for pressure measurement for electric propulsion testing [8].

Consistent with the approach taken in previous work on facility effects, the pressure in VTF-2 was controlled by a bleed flow of xenon propellant through an orifice located beneath the thrust stand. This location is identical to that used in previous H6 facility effects tests conducted by Reid; however, in this test, the orifice was oriented to inject flow axially in the downstream direction instead of radially as done by Reid [9]. The impact of bleed flow orientation on the results was explored in other work [10]. Average VTF-2 operating pressures for this work are shown as a function of the bleed flow rate in Table 1.

#### B. H6 Hall Effect Thruster

All experiments detailed in this work were performed using the H6 HET configured per Ref. [10].

#### C. Internal Bayard–Alpert Hot-Cathode Ionization Gauge

Measurements of the pressure (and thus number density) near the HET exit plane were acquired using a Granville–Phillips Stabil-Ion® Series 370 Bayard–Alpert hot-cathode ionization gauge mounted inside the test facility and connected to a Granville–Phillips Stabil-Ion Series 370 controller. The selected gauge and controller meet all of the design recommendations put forth in the best practices guide for pressure measurement for electric propulsion testing and are identical to those used in previous facility effects studies, thus allowing for direct comparison between datasets without needing to worry about variations between types of BA hot-cathode ionization gauges [8].

As shown in Fig. 1, the Stabil-Ion gauge was mounted to a Parker Daedal 200RT series rotary motion stage located approximately 0.5 m radially outward from the HET centerline and 0.1 m upstream of the HET exit plane. At each facility operating condition, measurements were taken with the gauge facing upstream and downstream to quantify the number densities associated with the positive and negative fluxes across the HET exit plane. To quantify the flux in the radial direction, and thus assess the validity of the one-dimensional flow assumption used to develop the background flow model, measurements were also taken for the gauge facing the HET (i.e., radially). The positional precision and uncertainty of the employed motion stage are $\pm 0.17$ deg and $\pm 1$ deg, respectively [2].

A detailed discussion of the sources of uncertainty for BA hot-cathode ionization gauges can be found in Ref. [8] and yields an uncertainty of 4–6% for all measurements taken with the in-chamber Stabil-Ion Series 370 gauge and 20–30% for the external pressure gauge.

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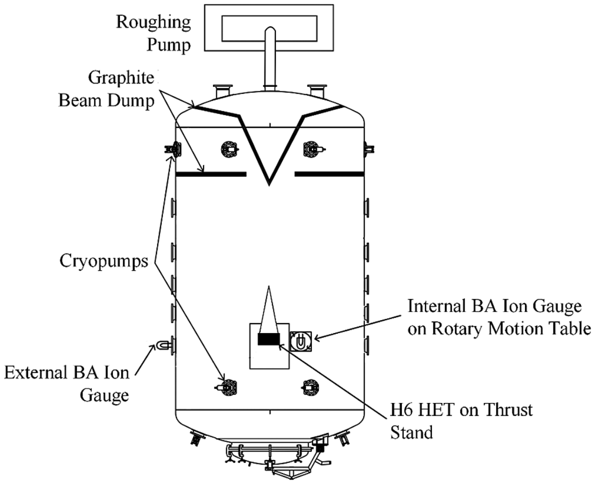



**Fig. 1 Schematic of VTF-2 (not to scale).**

**Table 1 VTF-2 operating pressures during this work**

| Bleed flow, mg/s | Operating pressure, $\mu$torr xenon |
|---|---|
| 0 | 11 |
| 5 | 13 |
| 12.5 | 17 |
| 20 | 21 |

## III. Model Modifications

Two modifications were made to the background flow model developed in previous work to adapt it to the empirical setup described in Sec. II [4]. During the original development of the background flow model, it was assumed that all particles injected into the vacuum test facility (regardless of source) traveled unimpeded to the downstream facility surfaces, thermalize, and reflect [4]. This assumption is applicable for facility configurations in which the bleed flow orifice is located either near the downstream facility surfaces or in the limit of low bleed flow rates. However, in this work, the bleed flow orifice was located near the HET exit plane and was used to axially inject mass flow rates of equal magnitude to the HET anode mass flow rate. Thus, to be ingested, these bleed flow neutrals (that now compose a significant fraction of the background flow field) must first survive an initial transit through the downstream regions of the facility without striking and sticking to a pump. The loss of neutrals during this initial transit is not captured by the assumptions regarding flow injection used in previous work and could contribute to an overestimation of the ingestion mass flow rate by the background flow model [4].

To correct for the loss of bleed flow neutrals during the initial downstream transit, the model was modified to separately account for the influx of particles into the test facility from the bleed flow orifice $n_{\text{bleed}}$. Following the approach used in Ref. [4], updated expressions for the number density and flux rates crossing the thruster exit plane in the upstream and downstream directions were developed to incorporate this modification. These updated expressions are shown in Eqs. (1–3):

$$n_{C+} = \frac{n_{\text{in}} + n_{\text{bleed}} - \alpha s_d n_{\text{bleed}}}{1 - (\alpha s_d - 1)^2(\alpha s_u - 1)^2} \tag{1}$$

$$n_{D+} = (1 - s_d)n_{C+} + (1 - \alpha)s_d n_{C+}\sqrt{T_w/T_p} \tag{2}$$

$$F_{D+} = mS_c n_{C+}V_w - m\ S_{p_d} n_{C+}V_w + (1 - \alpha)n_{C+}S_{p_d} mV_p\sqrt{T_w/T_p} \tag{3}$$

All variables used in Eqs. (1–3) retain their definitions from Ref. [4]. Equations (1–3) were derived by assuming that the bleed flow neutrals entered the modeling domain, traveling downstream at the thermal-diffusive speed characterized by chamber wall temperature.

The second modification to the model was done to more accurately describe the collisional processes impacting the bulk background flow. In the background flow model, the HET plume flow is assumed to collisionally scatter background neutrals traveling toward the HET exit plane, with cross sections computed by assuming the neutral density at the exit plane of all HETs is approximately $1 \times 10^{18}\ \text{m}^{-3}$, regardless of chamber condition [4,11]. The location of the bleed flow orifice in this work causes all injected bleed flow particles to enter the region downstream of the HET exit plane, and therefore contribute to the collisional scattering of the bulk background flow. Previous modeling work has shown that the injection of a bleed flow of approximately 35 mg/s increases the neutral number density on the order of $1 \times 10^{17}\ \text{m}^{-3}$ in the vicinity of the bleed flow orifice [12]. To account for this, the number density at the exit plane of the HET $n_{\text{exit}}$) was scaled as shown in Eq. (4):

$$n_{\text{exit}} = 1 \times 10^{18} + 0.1\frac{\dot{m}_{\text{bleed}}}{35} \times 10^{18} \tag{4}$$

This number density was then used to compute the collision cross sections using the same approach detailed in previous work [4]. The reader is referred to Refs. [4,10] for a more complete description of the background flow model development and sensitivities.

## IV. Results and Discussion

### A. Mean Discharge Current

Figure 2 shows measurements of the mean discharge current of the H6 operating with a fixed anode flow rate as a function of the bleed flow rate. Using the approach detailed in Ref. [4], measured changes in the mean discharge current can be used to approximate changes in the ingestion mass flow rate into the HET for a fixed anode flow rate. The ordinate in Fig. 2 therefore corresponds to the equivalent change in the ingestion mass flow rate computed from the measured change in discharge current relative to the no bleed flow case. A minimum of 10 measurements of the mean discharge current were acquired at each bleed flow rate, with each measurement encompassing approximately 400 fundamental periods. The empirical data shown in Fig. 2 represent the average across these 10 measurements, whereas the error bars correspond to the standard deviation.

Figure 2 also shows the change in the ingestion mass flow rate predicted by the background flow and thermal models. Consistent with previous work, the thermal model underpredicts the empirical

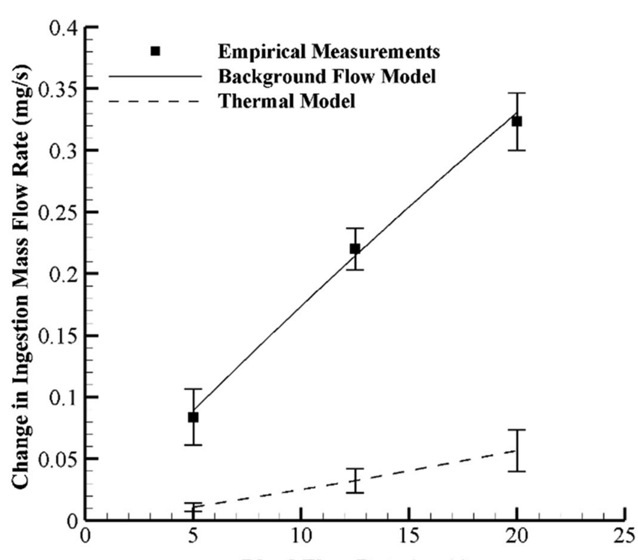



**Fig. 2 Change in H6 ingestion mass flow rate with bleed flow rate.**

results by 67–87%; and it is, on average, four times lower than the empirical measurements [9]. By contrast, the predictions of the background flow model match all empirical measurements to within the uncertainty. The background flow model thus yields results that are 75% closer to the empirical measurements than those of the thermal model.

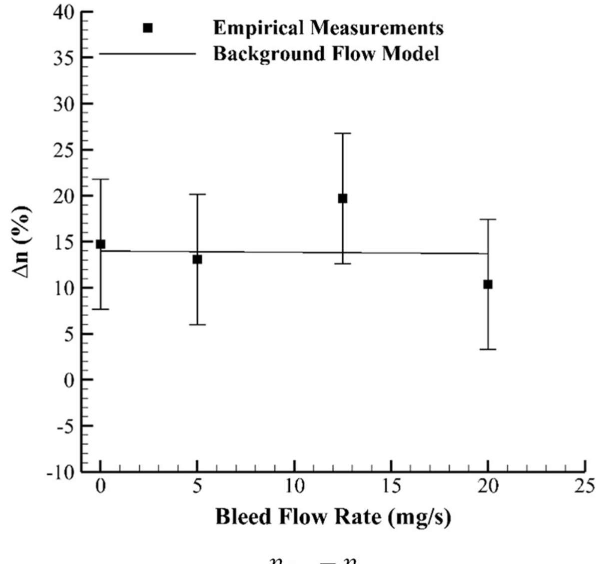
### B. Neutral Number Density

The background flow model predicts not only the flux rate of background neutrals but also the number density of neutrals traveling in the upstream and downstream directions. These quantities were directly measured using the internal ion gauge and used to compute the percent difference in number densities between the upstream- ($n_{D-}$) and downstream-facing ($n_{D+}$) orientations. This quantity ($\Delta n$) is shown as a function of the bleed mass flow rate in Fig. 3 along with the predictions of the background flow model.

The empirical results match what would be expected for a vacuum facility with a bulk axial flow of neutrals: the number density measured by the upstream-facing gauge is lower than that measured by the downstream-facing gauge because the background neutrals traveling in the downstream direction at the HET exit plane have gone through an additional two transits through the upstream pump region. The magnitude of this difference is, within the empirical uncertainty, identical to the predictions of the background flow model for all bleed flow rates.

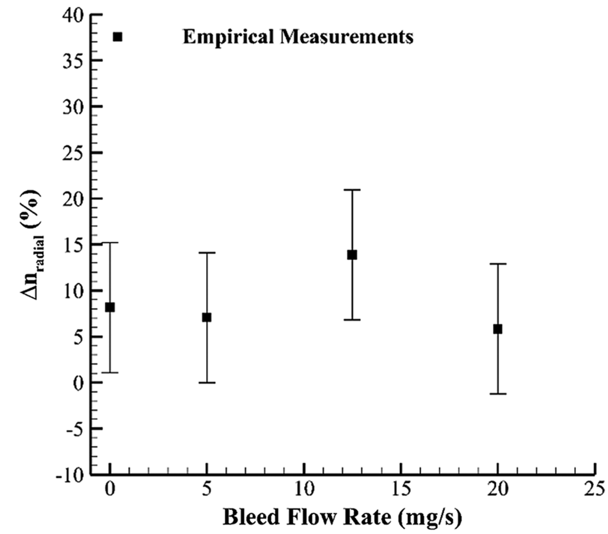
The one-dimensional flow assumption used to develop the background flow model neglects any bulk motion in the radial direction. To assess the validity of this assumption, measurements of the number density were taken with the Stabil-Ion gauge facing radially toward the HET. These measurements were used to compute the percent difference in number densities as measured by the ion gauge between the radial ($n_r$) and downstream-facing orientations ($n_{D-}$). This quantity ($\Delta n_{\text{radial}}$) is shown as a function of the bleed mass flow rate in Fig. 4.

As shown in Fig. 4, the number density of neutrals traveling radially is approximately 5–15% less than those traveling axially toward the H6 HET but 5% greater, on average, than the upstream-facing number density. This suggests that radial motion is an important component of the background neutral flowfield. Thus, a complete model of the background flowfield must be at least two-dimensional to capture both the radial motions due to sidewall collisions as well as the radial variation of background flowfield properties. Despite the significance of this radial motion in describing the overall flowfield, previous work has shown that it minimally contributes to HET neutral entrainment, and therefore negligibly impacts the predictions of the ingestion mass flow rate by the background flow model [4–6].




$$\Delta n = \frac{n_{D+} - n_{D-}}{n_{D-}}$$

**Fig. 3 Percent difference in upstream- and downstream-facing number densities with bleed flow rate.**




$$\Delta n_{\text{radial}} = \frac{n_{D+} - n_r}{n_r}$$

**Fig. 4 Percent difference in radial and downstream-facing number densities with bleed flow rate.**

## V. Conclusions

This work presented an empirical method for validating the previously developed background flow model of HET neutral ingestion. The original generalized model was adapted to describe the background flow environment in VTF-2 during the operation of the H6 HET and account for the injection of a large bleed flow along the thrust vector. The model predictions matched direct empirical measurements of the model outputs (i.e., ingestion mass flow rate and neutral number densities near the HET exit plane) to within the empirical uncertainty, which represents a 75% improvement in accuracy relative to the commonly applied thermal model. When combined with the findings of previous work, these results strongly suggest that the physical mechanisms captured by the background flow model do exist and offer a physical framework to explain the results observed in many previous facility effects studies [4].

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