JOURNAL OF PROPULSION AND POWER
Vol. 18, No. 4, July–August 2002

Facility Effects on Performance Measurements of Micropropulsion Systems that Utilize Gas Expansion

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Facilities can affect the measurement of spacecraft propulsion system performance in a variety of ways. In this study an underexpanded freejet is used to simulate experimentally a micropropulsion system such as those that operate on the expansion of propellant gases through nozzle geometries. Facility effects on the thrust measured by a torsion thrust stand installed in two facilities with distinctly different characteristics have been quantified over a steady-state thrust range from 10 to 480 μN. The two facilities varied in dimension and pumping capacity with background pressures ranging from 10^{-6} to 10^{-4} torr. In both facilities the measured thrust decreased with increasing facility background pressure. At a thrust level of 10 μN, the thrust decreased by approximately 20% at a facility background pressure of 2×10^{-4} torr relative to the thrust measured at 2×10^{-6} torr; however, a similar background pressure only resulted in a 4% reduction in thrust at 120 μN. The larger percent decrease in measured thrust for a given background pressure in the low thrust range has implications for the design of micropropulsion test facilities. The facility background pressure effect contributes to less than 2% error for the thrust range from 10 to 480 μN at background pressures less than 10^{-5} torr, suggesting that low background pressures are necessary for accurate thrust measurements below 500 μN. An empirical formulation based on background-plume penetration theory provides estimates of the thrust degradation as a function of facility background pressure. The empirical model fits the experimental data reasonably well for jet centerline values of the background gas radius of penetration into the freejet plume.

Nomenclature

A = area
A_{eff} = effective plenum area
C_B = background thermal velocity $= \sqrt{(8kT_B/\pi m_B)}$
C_D = orifice discharge coefficient
$c(\gamma)$ = constant, 0.161 ($\gamma = 1.67$), 0.0863 ($\gamma = 1.40$)
D = diameter
k = Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K
L_p = plenum radius
$\dot{M}$ = continuum mass flow rate $= \rho^* u^* A_j$
m = molecular mass
n = number density
p = pressure
r = radial position in plume
r_p = radius of penetration of background gas into plume
r_λ = mean free path of jet molecules in the undisturbed background gas $= (n_{B,\infty}\sigma_{jB})^{-1}$
T = temperature
$\Im$ = thrust
u = velocity
V_{rel} = relative velocity $= v_{j\infty} + C_B$
$v_{j\infty}$ = jet limit velocity $= \sqrt{[2\gamma/(\gamma-1)(kT_0/m_0)]}$
γ = ratio of specific heats
ε = correction factor to variable hard sphere collision cross-section
θ = angle from orifice centerline
σ = variable hard sphere collision cross section
ϕ = constant, 1.365 ($\gamma = 1.67$), 1.662 ($\gamma = 1.40$)

Subscripts

B = background
j = jet or orifice
sfc = along the plenum surface (that is, high θ)
0 = plenum or stagnation
∞ = undisturbed or limit

Superscript

$*$ = sonic conditions

Introduction

SPACECRAFT propulsion system performance is typically investigated in ground-based facilities, where the facility background pressure is orders of magnitude larger than ambient on-orbit conditions. Also, facility effects are not limited to background pressure level. There is some indication that the ratio of measured to on-orbit thrust can vary depending on the facility geometry, pumping configuration, thrust stand geometry, experimental setup, and the characteristics of the thruster and its corresponding exhaust plume.

Several authors have commented on the adverse effect of facility background pressure on experimental performance measurements for traditional spacecraft propulsion systems such as those that expand high stagnation pressure gases through nozzle geometries.[1–4] Additionally, several numerical simulations have shown the effect of facility background pressure on nozzle performance.[5–7] In all cases the measured thrust is shown to decrease as a function of increasing background pressure. The thrust degradation has been attributed to several factors. For example, Sovey et al.[1] indicate that flow separation in the nozzle with cold-gas propellants was responsible for the decrease in thrust at high background pressures. Manzella et al.[2] attributed the decrease in thrust to increased convective heat transfer in high-temperature resistojet nozzle expansions.

Low-thrust micropropulsion systems can be more susceptible to facility background chamber effects where very small changes in thrust can lead to significant errors. Because the majority of the facility background density comes from the thruster mass flow, a given facility is expected to be able to maintain lower background pressures when studying micropropulsion systems compared to

Presented as Paper 2001-3335 at the 37th Joint Propulsion Conference, Salt Lake City, UT, 9–11 July 2001; received 30 July 2001; revision received 29 October 2001; accepted for publication 4 February 2002.

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large-scale thruster investigations. This study shows that, for a given background pressure above 10^{-5} torr, the facility effect leads to significant errors at the low range of measured thrust. Facilities constructed to investigate micropropulsion system performance must have reasonable pumping to ensure background pressures below 10^{-5} torr during thruster operation, suggesting that simple scaling of a micropropulsion facility's pumping system based on the physical size of the facility might not be adequate.

This study investigates the effects of facility geometry and background pressure on thrust measurements several orders of magnitude lower than previous studies.[2–4] An underexpanded sonic orifice was used as a simplified cold-gas micropropulsion system. An empirical formulation based on background-plume penetration theory is provided to estimate the degradation in thrust as a function of facility background pressure. Although a generalized theory to predict the effects of a facility on the thrust measurements of particular propulsion systems might not be practical, a simplified framework is presented that appears to be an adequate initial step towards this end.

Analysis

An empirical model was developed to aid in the understanding of the facility background pressure effects on the measured thrust. Muntz, Hamel, and Maguire (MHM)[8] used a simple scattering formulation to describe the rarefaction of a source flow expanding into a finite but low background pressure. If the background pressure is sufficiently low, a shock wave is not evident in the interaction region between the source flow gas and the background. Rather, it is replaced by a rarefied flow scattering region where the background molecules diffuse into the high-velocity source flow. The distance from the source at which the background gas number density far from the source $n_{B,\infty}$ is reduced by a factor e^{-1} is called the radius of penetration by MHM[8] and is given by

$$r_p = (V_{\text{rel}}/C_B)\varepsilon\sigma_{\text{jB}} n^* r^{*^2} \tag{1a}$$

The collision cross section σ_{jB} is obtained from the equivalent variable hard-sphere collision diameters derived from viscosity data for the source and background gases. The source is characterized by the number density n^* at the sonic radius r^*. Following MHM,[8] ε is a parameter less than or equal to one, which accounts for any uncertainty regarding the number of model collisions required before an average background particle has effectively been turned around or stopped. It might also be considered as an adjustment to the collision cross section based on viscosity measurements, which certainly might not apply in the particular case of interest here. Using the work of Ashkenas and Sherman,[9] the source flow can be related to the underexpanded flow from a sonic orifice, and the expression for the radius of penetration becomes

$$r_p(\theta) = (V_{\text{rel}}/C_B)\varepsilon\sigma_{\text{jB}} n_{\text{j0}} c(\gamma) D_j^2 \cos^2(\pi\theta/2\phi) \tag{1b}$$

This formulation assumes the jet density varies as the square of the cosine of the angle from the orifice centerline[9] and that a source flow approximation applies, which requires $r_p \gg D_j$ so that $n_j \sim 1/r^2$.

The validity of the expression for the radius of penetration was examined in several papers.[10–13] MHM[8] followed up on their original work by examining the background gas penetration with a variety of underexpanded, sonic orifice jets expanding into finite background pressure environments. For the purposes of the present discussion, a large amount of data[10,11,13] and more rigorous theoretical extension of the original model[12] result in a value of $\varepsilon = 0.43$ on the orifice centerline ($\theta = 0$ deg) for the conditions of the experiments reported here. In the previously reported experiments, the background concentration measured included all molecules originally in the background so that the $\varepsilon = 0.43$ includes all scattered background molecules. Additionally, data reported in Brook et al.[12] (see Fig. 12 of Ref. 12) indicate that Eq. (1b) is only valid up to $\theta \approx 45$ deg. Beyond 45 deg the radius of penetration departs from the Eq. (1b) functional form and is still at a value of $r_p(\theta)/r_p(\theta = 0) = 0.25$ at $\theta = 80$ deg.

In the various experiments[10–13] the detailed shape of the background density as a function of distance and angle from the sonic orifice have been measured. The MHM[8] prediction for the concentration profile is

$$n_B(r,\theta)/n_{B,\infty} = \exp\{-[r_p(\theta)/r]\} \tag{2}$$

Providing the jet-background interaction is in the scattering regime, the measurements all indicate that the form exhibited in Eq. (2) is remarkably accurate.[10,11] The scattering regime is most conveniently indicated by the plume Knudsen number[12]

$$Kn_p = r_\lambda / r_p(\theta = 0) \geq 1 \tag{3}$$

The proposed mechanism for lower measured thrust as a function of increased background pressure is shown schematically in Fig. 1 (Ref. 14). The mechanism assumes that the effect of scattered jet molecules on the front surface of the orifice is independent of background pressure. For no orifice flow the background pressure exerts an equal force on the front and back sides of the orifice plenum (equilibrium). With flow introduced through the orifice, the resulting jet acts like an ejector pump similar to that of the oil vapor in a vacuum diffusion pump.[15] Collisional removal of the background gas by the orifice plume, as described quantitatively in the immediately proceeding paragraphs, results in a lower background pressure contribution on the jet side of the plenum than on the back side. The pressure difference exerts a force on the plenum in a direction opposite to the thrust vector produced by the jet. Because the gas density in the plume is relatively high compared to the background gas density in the vicinity of the orifice, the flow can effectively prevent background molecules from penetrating the orifice plume and striking a portion or all of the front surface of the plenum.[8] The change in thrust as a function of background pressure is given by

$$\Delta\Im = (\Im_{p_{B,\infty}}) - (\Im_{p_B}) = P_{B,\infty} A_{\text{eff}} \tag{4}$$

The effective area cleared of background gas A_{eff} is a way to measure the area providing a force that is opposite to the thrust vector.

The data presented in the literature on background gas penetration into underexpanded plumes at plume Knudsen numbers greater than unity[10–13] have been used to construct a visualization of the reduced background densities for the present experiments. The previous data selected were obtained using a circular base plate, containing the sonic orifice at its center, which was about $3r_p$ in radius. A set of data for $r_p(\theta)$ as a function of θ was used to determine the off-axis behavior of r_p at angles greater than 45 deg (Ref. 12). For the experiment reported here, the experimental setup was similar to that for which the off-axis background gas penetration data are available, except that for the thrust measurements the plenum size

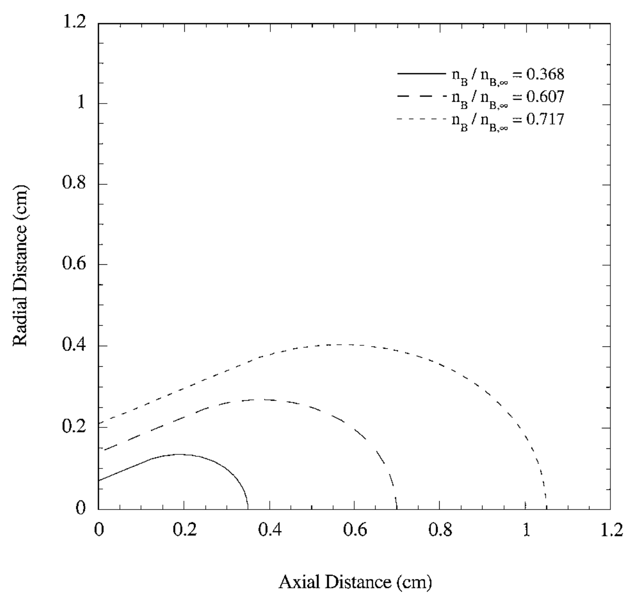

Fig. 1 Background pressure thrust degradation mechanism.

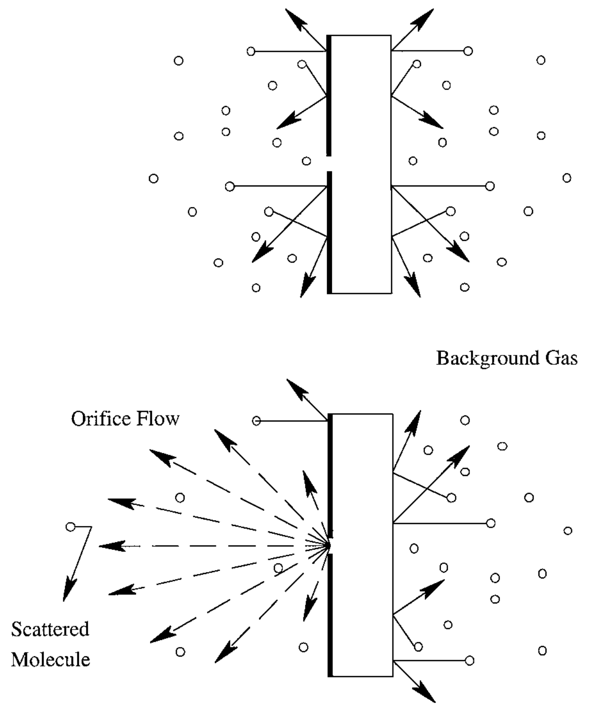

Fig. 2 Extent of background gas depletion for a 1.0-mm-diam orifice with a nitrogen stagnation pressure of 2.0 torr. The orifice plenum diameter is assumed to be approximately $3r_p$.

was generally larger than $3r_p$ by a factor of three or more. The effect of this difference is not known, but based on the analysis of Brook et al.[12] it would be expected to increase the high angle r_p as compared to a $3r_p$ radius base plate. The plot in Fig. 2 presents lines of constant $n_B/n_{B,\infty}$ for the nitrogen flow from a 1.0-mm-diam orifice with $p_0 = 2.0$ torr and a $3r_p$ diameter base plate. The jet-background interaction is assumed to be the limiting case of $Kn_p \gg 1$. Note the relatively large volume of reduced background gas concentration downstream of the plenum shown in Fig. 2.

To estimate the contribution of the disturbed background gas concentration to the pressure on the base plate, it is necessary to assume the form of the distribution function for the background gas. The earlier experiments only measured number density. Because the stagnation and background temperature were the same in the present experiments, it is reasonable to assume that the distribution functions correspond to an equilibrium distribution at the background and stagnation gas temperature of about 295 K. With this assumption the effective area A_{eff} can be expressed as

$$A_{\text{eff}} = 2\pi \int_0^{L_p} \left(1 - \frac{n_{B,\text{sfc}}}{n_{B,\infty}}\right) r\,\mathrm{d}r$$

or

$$A_{\text{eff}} = 2\pi \int_0^{L_p} \left[1 - \exp\left(-\frac{r_{p,\text{sfc}}}{r}\right)\right] r\,\mathrm{d}r \tag{5}$$

Combining Eqs. (4) and (5) yields

$$\Delta\Im = P_{B,\infty}\left\{\pi L_p^2 - 2\pi \int_0^{L_p} \left[\exp\left(-\frac{r_{p,\text{sfc}}}{r}\right)\right] r\,\mathrm{d}r\right\} \tag{6}$$

The change in thrust can be modeled with the appropriate selection of r_p. It is expected that an appropriate radius of penetration for the effective area is $r_{p,\text{sfc}}$ or the radius of penetration along the surface of the orifice plenum (that is, at $\theta = 90$ deg).

The thrust from a sonic orifice is given by[16]

$$\Im = C_D \dot{M} u^* + p^* A_j = p_0 A_j (1 + C_D \gamma)[2/(\gamma + 1)]^{\gamma/\gamma-1} \tag{7}$$

Earlier work[14] shows that the discharge coefficient varies from approximately 0.6 to 0.86 for the orifice and Reynolds-number range used in this study. It is assumed that the measured thrust stand deflection at a given stagnation pressure is related to a thrust calculated by Eq. (7) with an experimentally measured discharge coefficient and stagnation pressure.

Apparatus and Procedure

An underexpanded orifice was used to simulate a micropropulsion system. The orifice simplified the flow compared to a micronozzle geometry that might be used in a cold-gas, resistojet, or chemical microthruster.[17–19] The orifice was attached to a nano-Newton thrust stand, which was installed in two different vacuum facilities. The facilities differ in physical size, available pumping, and ultimate pressure ranges. The thrust stand deflection (force) was measured as a function of the orifice stagnation pressure and the facility background pressure. The background pressure in the facility came from three main sources: orifice operation, a background gas inlet, and external vacuum leaks.

The orifice had a diameter of $d_j = 1.0$ mm and a thickness of $t_j = 0.015$ mm yielding a $t/d = 0.015$. The orifice was machined by conventional means in a tantalum shim attached to an aluminum plenum. The rectangular plenum had dimensions of 65 mm in height, 35 mm in width, and 13 mm in thickness. Tantalum was used because accurately machined orifices could be manufactured in very thin shims without distortion or severe buckling of the material. A circular plenum with the same surface area as the rectangular plenum used in this study would have a radius of $L_p = 2.69$ cm. In the experimental setup one orifice plenum was attached to each arm of a torsion thrust stand such that the two thrust vectors point in opposite directions (that is, the thrust stand deflection is twice that of a single orifice). Nitrogen and helium were used as propellant and background gas.

Thrust Stand

The nano-Newton thrust stand has been optimized for operation with several micropropulsion systems currently in development.[17–19] Figure 3 shows the thrust stand installed in a vacuum chamber. Overall, a design approach was taken to develop a thrust stand that was simple to construct, modify, and operate. A torsion balance is perhaps the simplest configuration that can be utilized for steady-state and transient thrust measurements. Only steady-state thrust measurements are reported in this study. As shown in Fig. 3, the thrust stand is supported by two force restoring flexure pivots with a spring constant of 0.0016 Nm/deg. The thrust stand arms are approximately 25 cm long from the center of rotation.

The thrust measurements involve sensing the angular displacement resulting from a torque (thrust force multiplied by a radial distance) applied to a damped rotary system. The present method

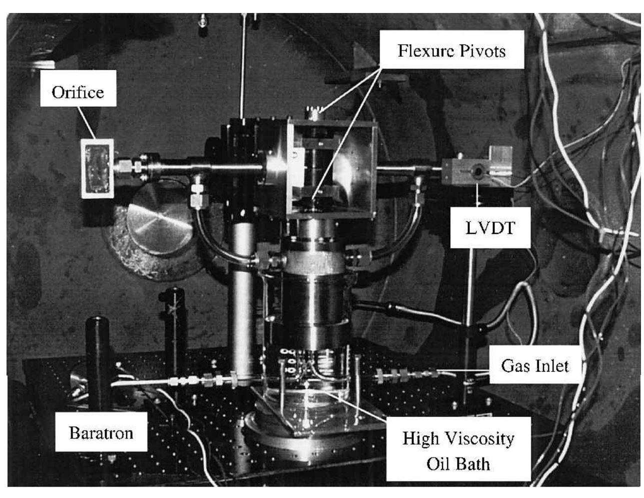

Fig. 3 Nano-Newton torsional thrust stand installed in the CHAFF-II facility.

for detecting angular deflection is to measure the linear displacement at a known radial distance using a linear variable differential transformer. The total linear movement of the arm is approximately 0.5 mm for a 500-μN thrust level, which corresponds to less than 0.1-deg angular deflection. Therefore, the measured deflection is assumed to have a linear relationship with the thrust produced. The detailed operational characteristics of this thrust stand are the topic of earlier work.[20]

Facilities

The thrust stand was similarly installed in two vacuum chambers of the Collaborative High Altitude Flow Facility (CHAFF) at the University of Southern California. CHAFF-II is a 0.86 m diameter by 1.5-m-long cylindrical vacuum chamber shown schematically in Fig. 4a. CHAFF-II is pumped by a 2000 L/s Roots blower system, which provides ultimate vacuum pressures of approximately 1.0×10^{4} torr. The background gas is introduced into CHAFF-II in two locations: on the top chamber flange and immediately before the first stage of the Roots blower system. The location of the thrust stand in CHAFF-II relative to the pumping system and the location of background inlets is shown in Fig. 4a. During the experiments, the background pressure was varied from 10^{-4} to 10^{-3} torr. Background pressures were measured with an ionization gauge system, which was calibrated in the 10^{-5} to 10^{-4} torr pressure range using a baratron capacitance manometer. The location of the background pressure measurement relative to the thrust stand and pumping port is also shown in Fig. 4a.

CHAFF-IV is a 3-m-diam by 6-m-long stainless-steel vacuum chamber shown schematically in Fig. 4b. Although CHAFF-IV is a cryogenically pumped, space simulation facility,[21] only a single diffusion pump was used in this study. The Zyrianka 900 diffusion pump has an ultimate pumping speed of 25,000 L/s for nitrogen and 42,000 L/s for helium. The ultimate facility pressure in CHAFF-IV was approximately 1.0×10^{-6} torr with a single diffusion pump operating. The CHAFF-IV ultimate pressure was two orders of magnitude lower than that of CHAFF-II. The 1.0-m-diam diffusion pump is backed with a 2000 L/s Roots blower system. The location of the thrust stand in CHAFF-IV relative to the pumping system and background inlet is shown in Fig. 4b. During experiments in CHAFF-IV, the background pressure was varied from 10^{-6} to 5×10^{-4} torr. In addition to the background pressure measurements on the chamber walls, the background pressure was also measured in the immediate vicinity of the thrust stand by two ionization gauges located inside the facility. The enclosed ionization gauges were oriented in various directions in an attempt to assess the background characteristics near the thrust stand caused by orifice operation and the injection of background gases into the facility.

Results and Discussion

CHAFF-II Results

Figure 5 shows the measured deflection for given orifice stagnation pressures as a function of the facility background pressure. The propellant and background gas is nitrogen. The parameters of the linear curve fits in Fig. 5a are given in Table 1. As expected, the absolute deflection for a given orifice stagnation pressure decreases with increasing background pressure. Assuming that the background pressure in front of the orifice plenum is zero, the force exerted on the backside of the orifice plenum ($A_p = 22.75$ cm^2) is approximately 100 μN for $p_B = 3.3 \times 10^{-4}$ torr. Because the order

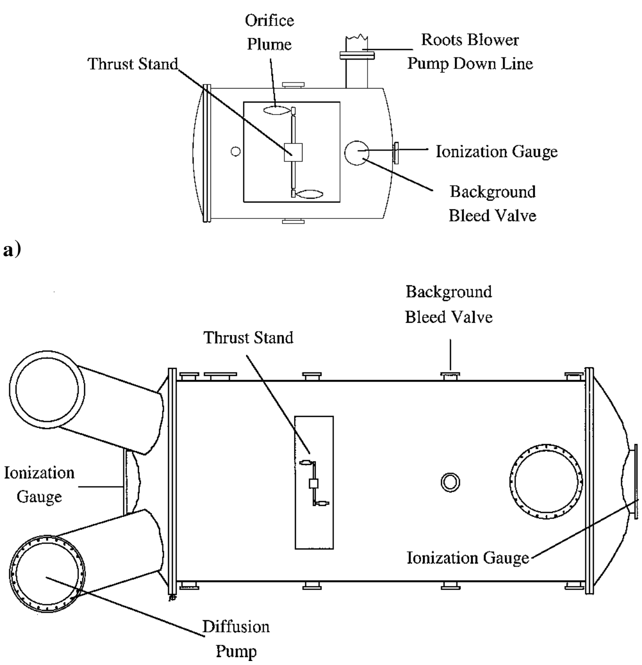

Fig. 4 CHAFF vacuum chambers showing placement of the thrust stand and experimental configuration: a) CHAFF-II and b) CHAFF-IV. (Note: Relative size of thrust stand to chamber is to scale; however, the facility dimensions are not to scale relative to each other).

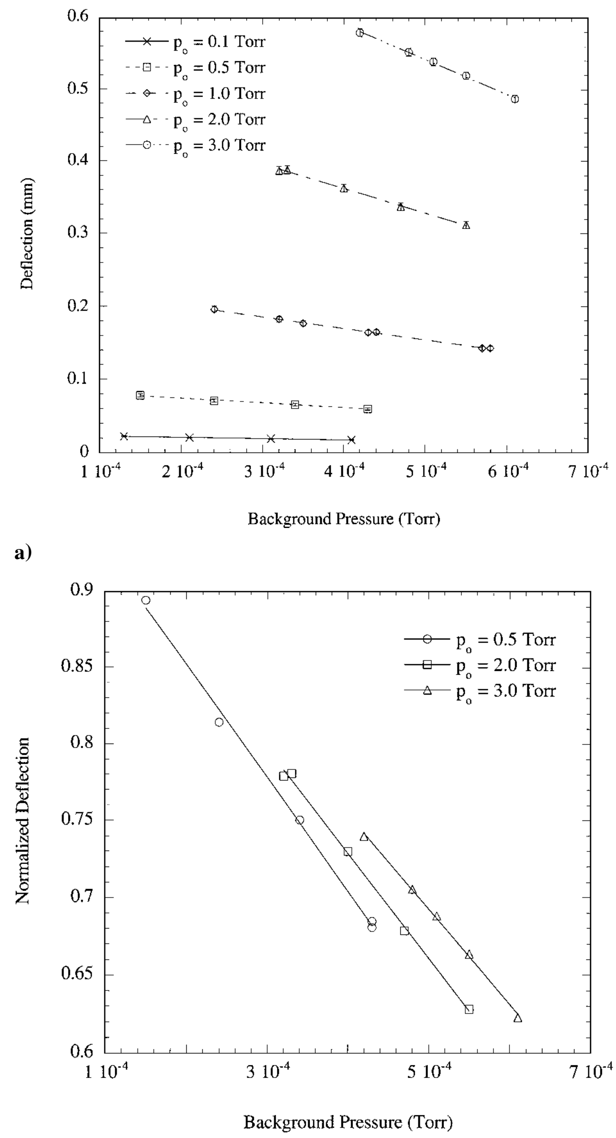

Fig. 5 Deflection as a function of CHAFF-II facility background pressure for nitrogen orifice flow into a nitrogen background: a) absolute deflection measurement as a function of stagnation pressure and b) deflection normalized by zero background pressure deflection (y-intercept from Table 1).

Table 1 Linear curve fit for CHAFF-II deflection measurements

p_0, torr	Linear slope	y-Intercept[a]
0.2	−17.542	0.02447
0.5	−64.192	0.08674
1.0	−158.23	0.23275
2.0	−336.52	0.49603
3.0	−481.27	0.78236

[a] y-intercept represents the zero background pressure deflection of the thrust stand.

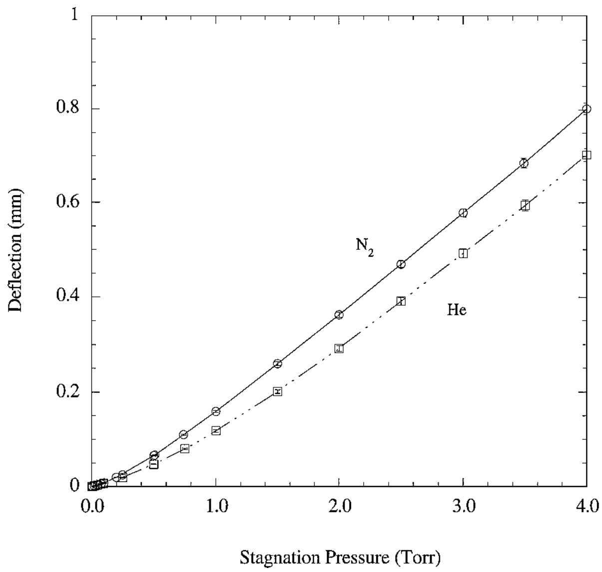

Fig. 6 Deflection vs orifice stagnation pressure for nitrogen and helium flows. Data obtained for lowest possible facility background pressure maintained during orifice operation in CHAFF-IV.

of magnitude of the effect can be the same or greater than that of the thrust being measured, the background pressure negative thrust effect could lead to significant measurement errors. Figure 5b shows the deflection normalized by the y-intercept of the linear data fit from Table 1. The y-intercept of the linear fit represents the deflection corrected for zero background pressure assuming a linear dependence. To first order, the change in thrust is linear over the range of CHAFF-II background pressure. The linear dependence assumption was validated for orifice flow using a direct simulation Monte Carlo (DSMC) numerical technique.[7]

The data suggest that the relative change in thrust increases for a given background pressure as the thrust level (or stagnation pressure) decreases. This effect can be critical for performance measurements of micropropulsion systems, which are expected to operate at low thrust levels. The deflection as a function of background pressure was independent of the location of the background gas injection into the facility suggesting that the thrust degradation effect is fully attributable to the facility pressure.

CHAFF-IV Results

Figure 6 shows the measured thrust stand deflection as a function of orifice stagnation pressure for nitrogen and helium propellants at the lowest maintainable CHAFF-IV background pressure. The measured deflections have a standard deviation of 6.65×10^{-3} and 10^{-2} for five runs on nitrogen and helium at $p_0 = 1.0$ torr, respectively. The statistical error was derived by taking the standard deviation of at least five deflection measurements at a given stagnation pressure. Based on the mean deflection of the stand, the statistical error was determined to be 0.59% for nitrogen and 0.95% for helium. In all, the standard deviations in measured thrust stand deflection are within 1% of the mean deflections over the range of stagnation pressures from 0.1 to 4.0 torr. Using the measured orifice discharge coefficients as a function of stagnation pressure from Ketsdever et al.[14]

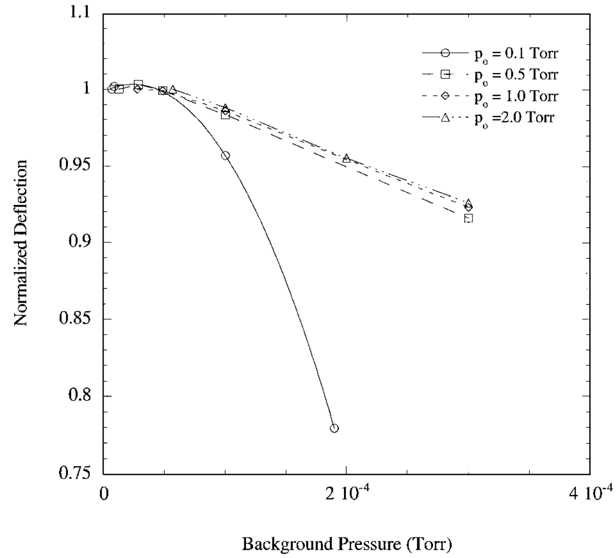

Fig. 7 Normalized deflection as a function of CHAFF-IV facility background pressure for nitrogen orifice flow into a nitrogen background.

and Eq. (7), the calculated thrust generated by nitrogen at $p_0 = 0.1$ and 4.0 torr is approximately 10 and 480 μN, respectively.

As the stagnation pressure in the orifice decreased toward the rarefied flow regime, the slope of the data in Fig. 6 transitions from a continuum to a rarefied value as discussed by Ketsdever et al.[14] This trend is evident because the ratio of the continuum solution for the thrust [Eq. (7)] to the free molecule thrust for a given stagnation pressure is approximately 2.3 for $\gamma = 1.4$ or 1.67. This suggests that the slope of the measured thrust should transition from a continuum value to a lower free molecule value as the stagnation pressure decreases.

Figure 7 shows the measured deflection for nitrogen as a function of facility background pressure for several stagnation pressures. At background pressures two orders of magnitude lower than in CHAFF-II, the measured thrust begins to asymptote at the lower facility background pressures. The results in Fig. 7 are normalized by the asymptotic limit. This approach differs from the CHAFF-II analysis because the data never asymptote at the lowest facility pressures in CHAFF-II; however, it is clear that the asymptotic normalization is physically more accurate than the linear approximation used with the CHAFF-II data. At a thrust level of 10 μN, the thrust decreased from the asymptotic value by approximately 20% at a facility background pressure of 2×10^{-4} torr; however, a similar background pressure only resulted in a 4% reduction in thrust at 120 μN. As indicated in Fig. 7, the facility background pressure effect contributes to less than a 2% reduction for the thrust range between 10 and 480 μN at background pressures less than 10^{-5} torr.

Thrust stand deflection as a function of facility background pressure is presented in Fig. 8 for helium flow into a helium background compared to a nitrogen flow into a nitrogen background. For the helium cases the background gas is composed of laboratory air to a level of approximately 1×10^{-6} torr. At the lowest background pressure for the $p_0 = 2.0$ torr case, the laboratory air comprises approximately $\frac{1}{4}$ of the background number density. Because the collision cross section for helium-nitrogen or helium-oxygen is larger than that of helium-helium, the effect of background gas depletion is expected to be larger for an air background. Because of the differences in the collision cross section, the change in thrust is expected to be larger for a nitrogen flow into a nitrogen background than for a flow of helium into a helium background. Figure 8 indicates this trend for $p_0 = 2.0$ torr.

Figure 9 shows the change in experimentally measured thrust and that expected from the background penetration empirical model of Eq. (6) for nitrogen and helium. The results obtained with Eq. (6) have been multiplied by a factor of two to account for the two orifices operating simultaneously in the experiment. For comparison with

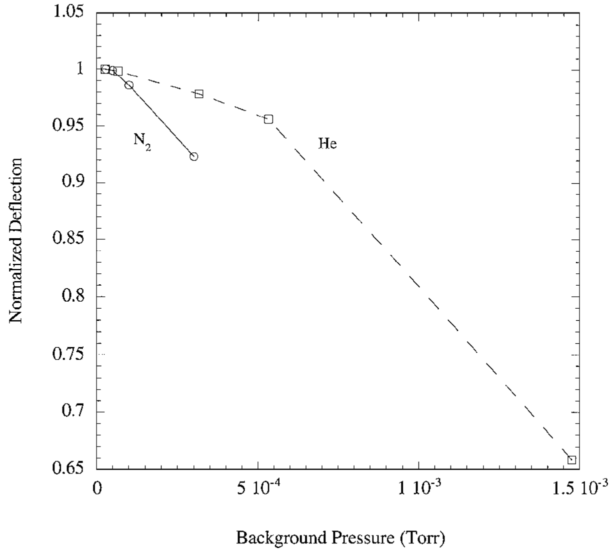

Fig. 8 Normalized deflection as a function of CHAFF-IV background pressure for nitrogen flow into a nitrogen background and helium flow into a helium background ($p_0 = 2.0$ torr).

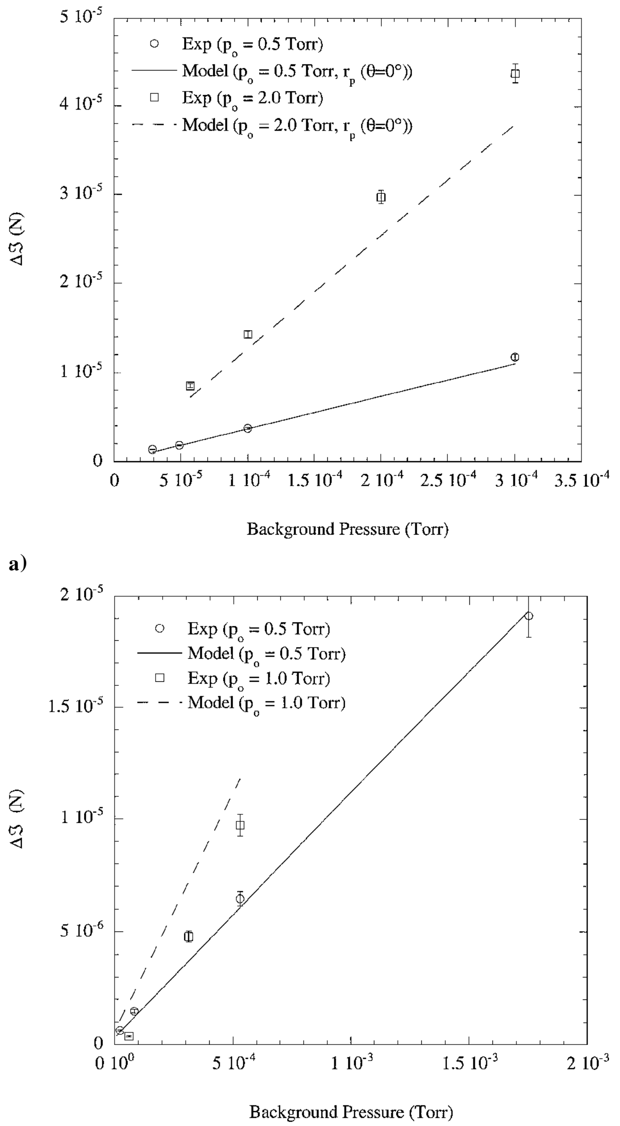

Fig. 9 Change in thrust for orifice flow vs CHAFF-IV background pressure for empirical model results and experimental data: a) nitrogen, b) helium [empirical model for $r_p(\theta = 0$ deg)].

the $\Delta\Im$ shown in Fig. 9a, nitrogen at $p_0 = 0.5$ torr and 2.0 torr results in thrust levels (at zero background pressure) of approximately 50 and 260 μN, respectively. The model formulation agrees with the experimental data for values of $r_{p,\mathrm{sfc}} = r_p(\theta = 0\ \mathrm{deg})$ for both nitrogen and helium flows to within a maximum of 15%. Preliminary DSMC results[7] show similar trends as the experimental data and empirical model as a function of facility background pressure; however, more detailed DSMC results are required before any direct comparisons can be made with the experimental data. For lower values of $r_{p,\mathrm{sfc}}$ such as those at large angles from the jet centerline ($\theta = 90$ deg), the model underpredicts the change in thrust as a function of background pressure; however, a high angle value of the radius of penetration is expected to be most appropriate for the proposed thrust degradation mechanism.

The fact that the empirical model does not reproduce the magnitude of the experimental results for high angle values of r_p indicates that the models miss some phenomenological feature of the actual flow. The discrepancy could be caused by several factors. First, the extent of the base plate in the experimental plenum is larger than in other experiments by which an appropriate r_p is being estimated. A larger base plate would act to increase the high angle radius of penetration. Second, the difference could also be caused by an induced flow caused by the injector pump effect of the background gas by the jet or by the injection of the background gas into the facility. Finally, the model relies on experimentally obtained background pressure measurements to first order. Errors caused by the location of the measurement could contribute to the discrepancy observed between the empirical model and the experimental results.

For the minimum achievable background pressures in CHAFF-IV, the maximum error in measured thrust is expected to be less than 1.5% even for the worst-case assumption in Eq. (6) of $r_{p,\mathrm{sfc}} = r_p(\theta = 0\ \mathrm{deg})$. The orifice mass flow is found to be a constant over the range of facility background pressure investigated in both facilities, which is consistent with the background penetration model developed in this study. This implies that any error associated with the thruster specific impulse is driven only by the change in thrust.

Discussion

A comparison of thrust stand deflection in the CHAFF-II and CHAFF-IV facilities is given in Fig. 10. The normalized deflection is presented as a function of facility background pressure for nitrogen. For the CHAFF-II data the deflection has been normalized by the linearly extrapolated deflection at zero background pressure. Because the CHAFF-IV data asymptotes to a deflection value, the asymptotic limit is used for normalization. Because the data in CHAFF-II (Fig. 5) never asymptote at the lowest background pressures

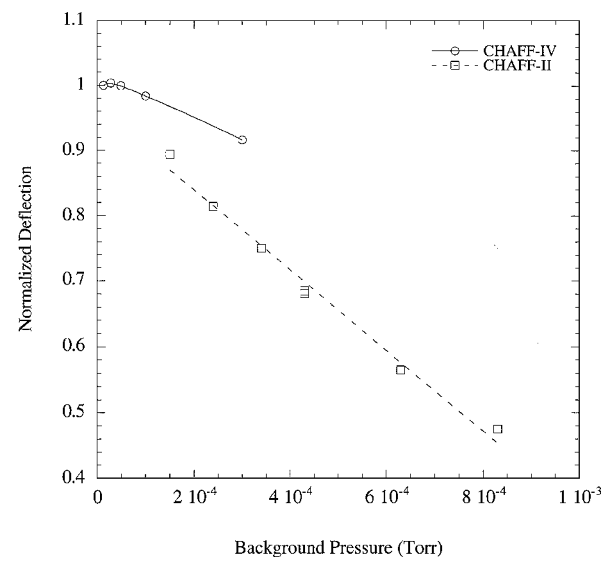

Fig. 10 Comparison of the normalized deflection as a function of background pressure between CHAFF-II and CHAFF-IV. Orifice operating with a nitrogen gas at $p_0 = 0.5$ torr.

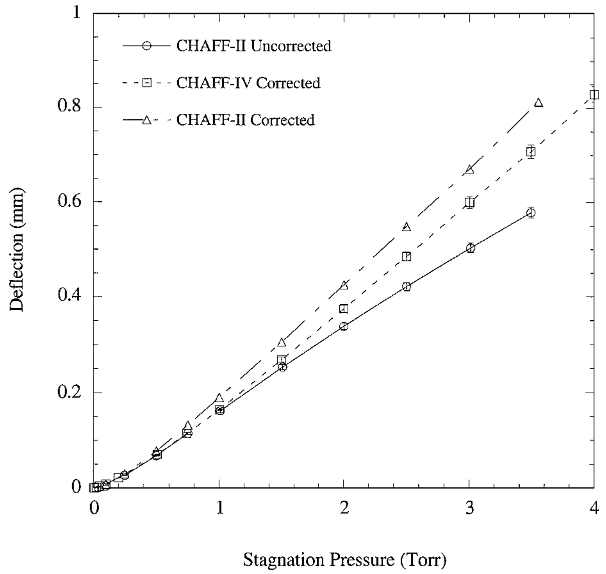

Fig. 11 Comparison of the CHAFF-II and CHAFF-IV deflection as a function of orifice stagnation pressure at each facility's lowest maintainable background pressure with a nitrogen orifice flow.

maintained, normalization cannot be performed in the same manner as with CHAFF-IV. A rather large difference in the deflection is seen between the two facilities even at the same background pressure. The difference is most likely a result of interactions between facility surfaces and the jet expansion. The location of the background pressure measurement is also critical. The thrust stand reacts to the local background pressure in the vicinity of the orifice plenums. Large gradients in the background pressure might exist in the CHAFF-II configuration because of the nature of the orifice flow and the pumping arrangement, resulting in higher background pressures in the vicinity of the thrust stand than measured near the pumping port. This effect would be consistent with the view of thrust degradation at higher background pressure.

Figure 11 shows the deflection as a function of nitrogen stagnation pressure for CHAFF-II and CHAFF-IV. The deflection in Fig. 11 represents the lowest maintainable background pressure in each facility with the orifices operating. The corrected CHAFF-IV deflection lies between the CHAFF-II uncorrected and corrected deflections. This is expected because the CHAFF-II corrected deflection assumes a linear correction to zero background pressure, whereas the CHAFF-IV data suggest that the deflection actually asymptotes at low background pressures. Therefore, the linear assumption should overcorrect the data. The implication of the results in Fig. 11 is that accurate thrust measurements can only be obtained in a background pressure regime where the thrust asymptotes to a zero background level because simplified corrections are not adequate.

Conclusions

The measured thrust of an underexpanded orifice has been shown to decrease with increasing facility background pressure independent of the facility geometry. However, the magnitude of the decrease for a given background pressure has been shown to be facility dependent. Although the trend in thrust degradation has been observed in several previous studies, this trend has been confirmed for the first time at thrust levels below 0.5 mN. Low-thrust micropropulsion systems are more susceptible to facility background chamber effects as compared to large-scale propulsion systems. For a given background pressure the facility effect leads to significantly larger errors at the low range of measured thrust when compared to higher thrust levels. At a thrust level of 10 μN in the CHAFF-IV facility, the thrust decreased from the asymptotic (or low background pressure) value by approximately 20% at a background pressure of 2×10^{-4} torr; however, a similar background pressure only caused a 4% reduction in thrust at 120 μN.

Experimental thrust measurements were made with the same thrust stand similarly installed in two facilities with distinctly different dimensions and pumping configurations. The differences in the data suggest that the facility characteristics such as physical dimensions and pumping system configuration are important in determining the magnitude of the thrust degradation. Based on the standard deviation of several measurements, the errors associated with the thrust stand deflection in CHAFF-IV are less than 1% over the range of orifice stagnation pressures from 0.1 to 4.0 torr. As evident from the CHAFF-IV results, the facility background pressure effect contributes to less than a 2% reduction for the thrust range between 10 and 480 μN at background pressures less than 10^{-5} torr.

A simple empirical model was used to give a reasonable approximation for the thrust degradation expected in this study. The empirical model compared reasonably well to the experimental thrust degradation data for the radius of penetration on the jet centerline ($\theta = 0$ deg). The empirical model was also shown match the trend in thrust degradation predicted by direct simulation Monte Carlo simulations. The fact that the empirical model does not fit the experimental data for more reasonable values of r_p indicates that some process is adding to the thrust degradation as a function of background pressure that the model does not include or reproduce. However, the general form of the empirical model has been shown to match the experimental trend and fit the experimental data to within 15% over the range of background pressures in this study.

To estimate the thrust degradation effect as a result of facility background pressure for a general case, the empirical model can be used with a radius of penetration value on the propulsion system centerline ($\theta = 0$ deg). For a general case this approach will act as an order of magnitude estimate. A configuration (small L_p and low $p_{B,\infty}$) yielding a negligible change in thrust for a value of r_p at $\theta = 0$ deg will, in all likelihood, produce an accurate thrust measurement.

Acknowledgments

This work was supported in part by the U.S. Air Force Office of Scientific Research and the Propulsion Directorate of the Air Force Research Laboratory at Edwards Air Force Base, California. The author also wishes to thank E. P. Muntz for his guidance, intuition, and assistance, and Andrew Jamison for his invaluable assistance with this research.

References

[1]Sovey, J., Penko, P., Grisnik, S., and Whalen, M., "Vacuum Chamber Pressure Effects on Thrust Measurements of Low Reynolds Number Nozzles," *Journal of Propulsion and Power*, Vol. 2, No. 5, 1986, pp. 385–389.

[2]Manzella, D., Penko, P., De Witt, K., and Keith, T., "Test-Cell Pressure Effects on the Performance of Resistojets," *Journal of Propulsion and Power*, Vol. 7, No. 2, 1991, pp. 269–274.

[3]Yoshida, R., Halbach, C., and Hill, C., "Life Test Summary and High-Vacuum Tests of 10-mlb Resistojets," *Journal of Spacecraft and Rockets*, Vol. 8, No. 4, 1971, pp. 414–416.

[4]Kanning, G., "Measured Performance of Water Vapor Jets for Space Vehicle Altitude Control Systems," NASA TN-D-3561, Aug. 1966.

[5]Chung, C., De Witt, K., Stubbs, R., and Penko, P., "Simulation of Low-Density Nozzle Plumes in Non-Zero Ambient Pressures," AIAA Paper 94-0357, Jan. 1994.

[6]Boyd, I., Jafry, Y., and Beukel, J., "Particle Simulations of Helium Microthruster Flows," *Journal of Spacecraft and Rockets*, Vol. 31, No. 2, 1994, pp. 271–277.

[7]Alexeenko, A., Levin, D., Gimelshein, S., Ivanov, M., and Ketsdever, A., "Numerical and Experimental Study of Orifice Flow in the Transitional Regime," AIAA Paper 2001-3072, June 2001.

[8]Muntz, E. P., Hamel, B., and Maguire, B., "Some Characteristics of Exhaust Plume Rarefaction," *AIAA Journal*, Vol. 8, No. 9, 1970, pp. 1651–1658.

[9]Ashkenas, H., and Sherman, F., "The Structure and Utilization of Supersonic Free Jets in Low Density Wind Tunnels," *Proceedings of the 4th International Symposium on Rarefied Gas Dyanamics*, Vol. 2, edited by J. DeLeeuw, Academic Press, New York, 1966, pp. 84–105.

[10]Muntz, E. P., and Maguire, B., "An Experimental Study of the Rarefaction of Underexpanded Jets," *Proceedings of the 7th International Symposium on Rarefied Gas Dynamics*, Vol. 1, edited by D. Dini, C. Cercignani, and S. Nocilla, Editrice Tecnico Scientifica, Pisa, Italy, 1971, pp. 619–626.

[11] Muntz, E. P., Hamel, B., and Scott, P., "A Study of a Background Gas Penetration Into Underexpanded Jets and the Resulting Separation of Gas Mixtures," *Entropie*, Vol. 7, No. 42, 1971, pp. 28–32.

[12] Brook, J., Hamel, B., and Muntz, E. P., "Theoretical and Experimental Study of Background Gas Penetration into Underexpanded Free Jets," *Physics of Fluids*, Vol. 18, No. 5, 1975, pp. 517–528.

[13] Deglow, T., "Background Gas Mixture Penetration of Underexpanded Jets with Application to Isotope Separation," Ph.D. Dissertation, Dept. of Aerospace Engineering, Univ. of Southern California, Los Angeles, CA, June 1977.

[14] Ketsdever, A., Green, A., and Muntz, E. P., "Momentum Flux Measurements from Under Expanded Orifices: Applications for Micropropulsion Systems," AIAA Paper 2001-0502, Jan. 2001.

[15] Rebrov, A., "Studies on Physical Gas Dynamics of Jets as Applied to Vacuum Pumps," *Proceedings of the 15th International Symposium on Rarefied Gas Dynamics*, Vol. 2, edited by V. Boffi and C. Cercignani, B. G. Teubner, Stuttgart, Germany, 1986, pp. 455–473.

[16] Humble, R., Henry, G., and Larson, W., *Space Propulsion Analysis and Design*, 1st ed., McGraw–Hill, New York, 1995, p. 140.

[17] Ketsdever, A., Wadsworth, D., and Muntz, E. P., "Predicted Performance and Systems Analysis of the Free Molecule Micro-Resistojet," *Micropropulsion for Small Spacecraft*, Vol. 187, edited by M. Micci and A. Ketsdever, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, pp. 167–183.

[18] Mueller, J., Chakraborty, I., Bame, D., and Tang, W., "Vaporizing Liquid Microthruster Concept: Preliminary Results of Initial Feasibility Studies," *Micropropulsion for Small Spacecraft*, Vol. 187, edited by M. Micci and A. Ketsdever, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, pp. 215–230.

[19] Janson, S., and Helvajian, H., "Batch-Fabricated Microthrusters: Initial Results," AIAA Paper 96-2988, July 1996.

[20] Jamison, A., Ketsdever, A., and Muntz, E. P., "Accurate Measurement of Nano-Newton Thrust for Micropropulsion System Characterization," International Electric Propulsion Conf., Paper 01-0236, Oct. 2001.

[21] Ketsdever, A., "Design Considerations for Cryogenic Pumping Arrays in Spacecraft-Thruster Interaction Facilities," *Journal of Spacecraft and Rockets*, Vol. 38, No. 3, 2001, pp. 400–410.