Technical Notes

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Vacuum Chamber Pressure Maps of a Hall Thruster Cold-Flow Expansion

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Introduction

SEVERAL investigations are underway to model numerically[1,2] thruster performance and the interactions between Hall thruster plumes and spacecraft. The results of these models are highly dependent on the boundary conditions used. For simulations of laboratory experiments, one of the most important auxiliary inputs required by these codes is the background pressure of a laboratory vacuum chamber.[1] In addition, a key physical parameter in such simulations is the probability that a xenon atom incident on a cryogenic pumping panel actually sticks to the panel. This paper reports on a neutral background pressure map of a vacuum chamber that is used to validate existing models and verify sticking coefficient assumptions experimentally. This paper also shows that, for a reasonable range of values for the sticking coefficient, excellent agreement between simulation and experiment is obtained for several different cold flow conditions. The results will aid in the development of tools to facilitate the simulation of the interactions between Hall thruster plumes and spacecraft. Note that throughout the paper, we use the phrase cold flow to denote xenon flowing through the thruster anode and cathode without a plasma discharge and hot flow to denote xenon flowing through the anode and cathode of an operating thruster.

Background

The finite pressure present in a vacuum chamber can have a number of undesirable effects on the measurement of performance and plume characteristics of Hall thrusters.[1] High-energy exhaust particles interact with the neutral background particles through charge exchange collisions (CEX).[3,4] In the plume, the effects of CEX products are most evident in the perimeter, where they lead to an increase in the measured current density. At elevated background pressures, residual gas particles can be entrained into the thruster discharge region, artificially increasing engine thrust.[5] One approach that is routinely applied to correct performance data for ingested flow is to extrapolate thrust vs pressure data to zero background pressure.[6] Elevated background pressure has been found to increase the width of the ion energy distribution function through elastic collisions between beam ions and neutral background particles.[7] Because of these effects, the validity of comparisons made between data taken in facilities with different background pressures, especially at 10^{-2} Pa (10^{-4} torr) and higher, is questionable.[8] However, comparisons continue to be made between data taken in vacuum chambers with background pressures that differ by orders of magnitude.[9] Because of the drastic implications of facility effects, electric propulsion technology has reached the point where standard guidelines must be developed for test facilities to ensure reliable engine development and testing. This need has become even more pressing now that very high-power Hall thrusters are being developed.[10]

To provide high-fidelity data to the models that simulate the interaction between the Hall thruster plume and spacecraft, we must first correct the experimental performance and plume data for facility effects. To take a step in the development of a tool that is necessary to begin to understand and properly correct for facility effects, the neutral gas background pressure of the Large Vacuum Test Facility (LVTF), located at the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL), is mapped for a series of cold anode flow rates corresponding to Hall thruster operation conditions of 1.5, 3.0, and 9.0 kW, all at 300 V.

The cold flow results are used to validate a numerical model of the LVTF with a cold-flowing Hall thruster. This computational model employs the direct simulation Monte Carlo method (DSMC) that includes the chamber walls and cryopumps. In the current investigation, the results of the cold-flow pressure map are compared to the numerical simulation of the chamber to develop the tools necessary to correct for facility effects.

Experimental Study

Vacuum Facility

All experiments are conducted in the LVTF, shown schematically in Fig. 1. The thruster is mounted at thruster station 1. The LVTF is a stainless steel clad vacuum chamber that has a diameter of 6 m and a length of 9 m. Two blowers, each with a pumping speed of 940 l/s and four 190 l/s mechanical pumps evacuate the LVTF to moderate vacuum 4–13 Pa. To reach high vacuum, the LVTF is equipped with seven CVI TM-1200 reentrant cryopumps, each of which is surrounded by a liquid nitrogen (LN_2) baffle. The combined pumping speed of the facility is 500,000 l/s on air and 240,000 l/s on xenon with a base pressure of 2.7×10^{-5} Pa (2×10^{-7} torr). At the average anode flow rates investigated, 5.25, 10.46, and 14.09 mg/s, all with a 0.92 mg/s cathode flow, and at a nominal xenon pumping speed of 240,000 l/s, the operating pressures of the LVTF are approximately 2.3×10^{-4} (1.7×10^{-6}), 1.0×10^{-3} (7.7×10^{-6}), and 1.3×10^{-3} Pa (1.0×10^{-5} torr) on xenon.

Chamber pressure is monitored by two hot-cathode ionization gauges, as indicated in Fig. 1. The first gauge is a Varian model Bayard–Alpert (BA) gauge with a HPS model 919 hot-cathode controller. The BA model 571 ionization gauge is connected to the chamber via a 25 cm long by 3.48 cm inner diameter tube. The second is a Varian model UHV-24 nude gauge with a Varian UHV senTorr vacuum gauge controller. The UHV-24 nude gauge is calibrated for air by the manufacturer. Pressure measurements from both gauges are corrected for xenon using the known base pressure

Received 26 September 2003; accepted for publication 22 February 2004.

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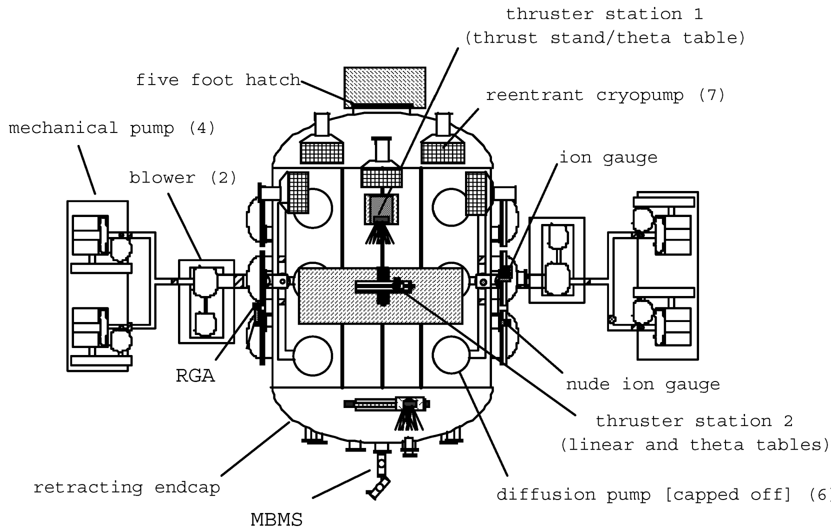


Fig. 1 Schematic of LVTF.

on air and a correction factor of 2.87 for xenon according to the following equation[11]

$$P_c = (P_i - P_b)/2.87 + P_b \tag{1}$$

where P_c is the corrected pressure on xenon, P_b is the base pressure, and P_i is the indicated pressure when xenon is flowing into the vacuum chamber. The corrected average pressure of the two gauges is normally reported as the chamber background pressure. All pressures reported in the following Paragraphs are corrected for xenon.

Hall Thruster

All experiments are performed on the NASA-173M version 1 (V1) 5-kW laboratory-model Hall thruster. The V1 shares many of the dimensions and design features of the well-characterized P5 thruster.[7,12] Like the P5, the V1 has a mean diameter of 148 mm, a channel width of 25 mm, and a nominal power rating of 5 kW. A more detailed description of the thruster may be found in Ref. 13.

A NASA John H. Glenn Research Center laboratory-model hollow cathode is located at the 12 o'clock position on the thruster. The cathode orifice is located approximately 25 mm downstream and 25 mm radially away from the outer front pole piece at an inclination of 30 deg from thruster centerline.

High-purity (99.999% pure) xenon is fed to the Hall thruster from compressed gas bottles through stainless steel feed lines. Anode and cathode propellant flows are controlled and monitored with MKS 1179A mass flow controllers. The flow controllers are calibrated with a custom apparatus that measures gas pressure and temperature as a function of time in an evacuated chamber of known volume. The mass flow controllers have an accuracy of ±1% full scale.

Ionization Gauges

The BA hot-cathode ionization gauge measures pressure over the range from 10^{-2} (10^{-4}) to 10^{-10} Pa (10^{-12} torr) with an accuracy of ±30% as reported by Varian. Estimates of the pressure for the experiment are from 10^{-3} (10^{-5}) to 10^{-6} Pa (10^{-8} torr), based on previous experimental data taken by the wall gauges. Because of its accuracy over the anticipated range of pressures, the BA gauge is chosen to measure the chamber pressure field.

Five Varian 571 BA-type standard range ionization gauge tubes are used to measure the chamber pressure field because of their rugged construction, low cost, and long life. Because follow-on work at PEPL includes pressure maps of the LVTF when the thruster is operating, the BA gauges utilize a neutralizer to ensure that the background chamber plasma does not affect pressure measurements. To make the hot- and cold-flow experiments identical in setup, the neutralizers are also used during the cold-flow experiment. The neutralizer design prevents plume ions from having a direct line of sight to the ionization gauge filament. Ions that enter the neutralizer are neutralized by a wall collision before entering the gauge. The neutralizer contains two 72 mesh screens (0.5 by 0.5 mm and 1.0 mm thick) that are floating to ensure neutralization of any ions that travel inside the orifice that are not neutralized by the grounded walls of the neutralizer body. Figure 2 shows the Varian 571 BA ionization gauge and the neutralizer along with their mounting position with respect to the anode flow direction.

Calibration of the five ionization gauge systems is performed by the Helium Leak Testing, Inc., Calibration Laboratory. Each system, comprised of a BA gauge, the actual internal and external cables used in the LVTF mapping, a Varian 10-wire vacuum chamber instrumentation feedthrough, and a Varian BA circuit board mounted in either the senTorr or multigauge controller, is calibrated with xenon as a one-piece unit using a National Institute of Standards and Technology traceable Leybold-Heraeus Viscovac VM211 spinning rotor viscosity gauge.

To generate the two-dimensional map inside the vacuum chamber, the ionization gauges are mounted to a two-axis positioning stage comprised of a 1.8-m-long linear stage in the radial direction that is mounted on a 0.9-m-long axial stage both with an absolute linear position accuracy of 0.15 mm. The ionization gauge positioning system (IGPS) is mounted to the positioning stage and carries the five BA gauges used to map the chamber. The IGPS allows the pressure measurements to be taken throughout the majority of the chamber with a single evacuation cycle of the LVTF. The locations mapped by the IGPS cover an area with a minimum distance from the thruster of 0.5 m, encompassing the typical 1 m distance at which plume properties are measured. Pressures closer than 0.5 m exceed the shutdown limit of the ionization gauge controller.

Figure 3 shows the LVTF and the 25 by 25 cm square grid on which data points are taken. The solid circles indicate the position of each of the five probes when the IGPS is in the initial position. Gauge 2 is positioned on the opposite side of the chamber centerline to avoid wake effects from gauge 3. Figure 3 also shows the coordinate system used for this experiment and the numerical simulation. The coordinate system origin is located at the discharge chamber exit plane on the thruster centerline.

Numerical Study

Computational analyses of Hall thruster plumes are regularly performed using a hybrid DSMC–particle in cell (PIC) formulation, for example, as in Refs. 14–16. The DSMC method[17] models the collisions of the heavy particles (ions and atoms). The PIC method[18] models the transport of the ions in electric fields. A hybrid approach is used in which the electrons are modeled using a fluid description. The DSMC code used in the present analysis has been validated for cold xenon flows previously as described in Ref. 19. In the present study, we apply an existing axially symmetric DSMC–PIC code developed specifically for Hall thruster plumes.[16] Atom–atom collisions employ the variable hard sphere (VHS) model[17] and isotropic scattering is assumed.

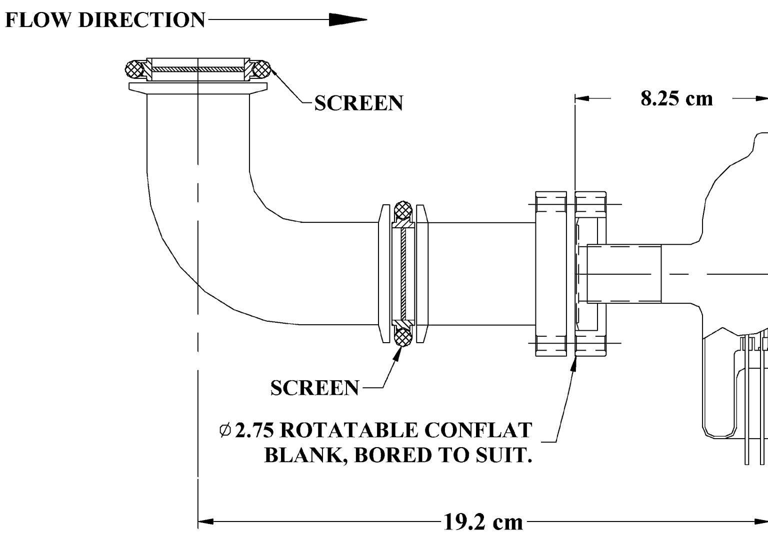


Fig. 2 Schematic of the Varian 571 BA ionization gauge connected to the neutralizer.

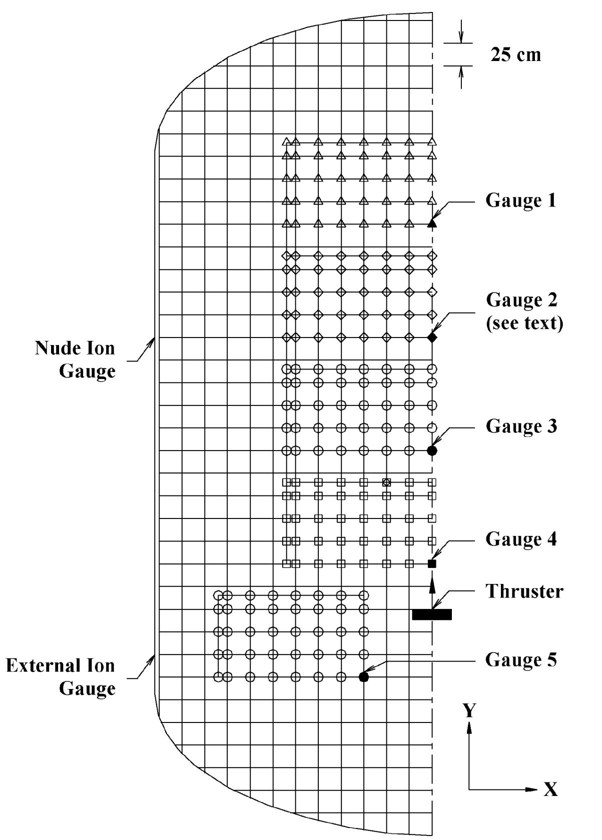


Fig. 3 LVTF half-plane (looking down) with the IGPS and 25 by 25 cm square grid: ○, location of a data point.

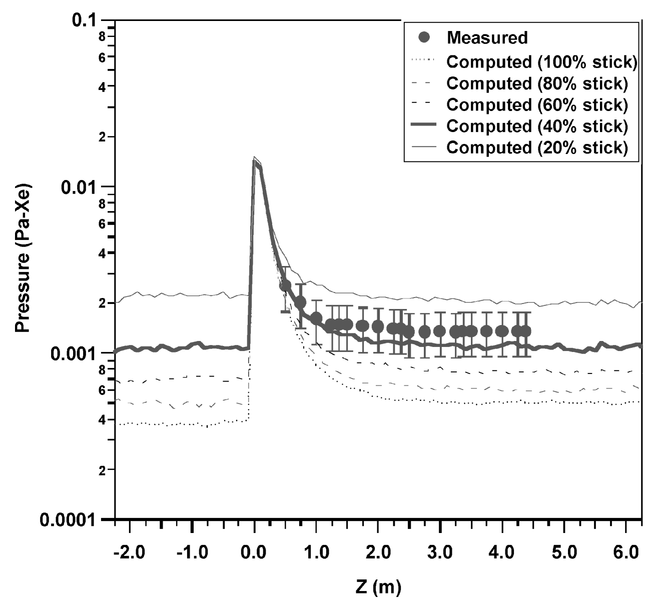


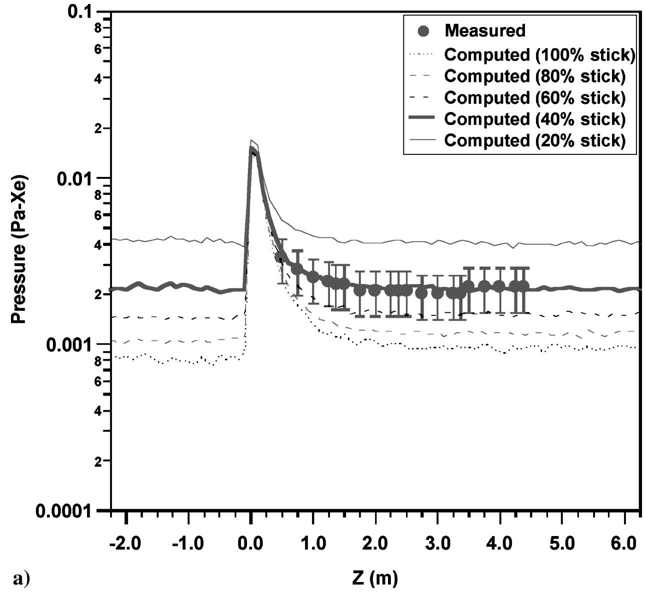
Fig. 4 Comparisons of simulated and measured pressure distribution within the LVTF for cold-flow operation of the NASA-173Mv1 Hall thruster at 10.46 mg/s flow rate and 240,000 l/s pumping along the thruster centerline.

In the model, the LVTF is represented as a cylinder of length 9 m and diameter 6 m. In these cold-flow simulations, the PIC steps are of course not applied. The walls of the chamber are modeled assuming fully diffuse reflection at a temperature of 300 K. The LVTF is equipped with seven cryopumps that are grouped into two sets: 1) four end pumps with a total pumping area of 4.15 m^2 and 2) three top pumps with a total pumping area of 3.11 m^2. In the simulations, the total area of each of these two sets is represented by a single pumping surface located in the vicinity of the actual pumps. The temperature of the pumping surfaces is assumed to be 15 K, which is representative of the actual cyrosurface temperature. There are no data for the sticking coefficient of xenon on cryogenic panels; however, data for other noble gases indicate a range of 0.6–0.8 (Ref. 20). These are values for a flux of gas onto bare cryosurfaces. Because the pumps installed in the LVTF are surrounded by liquid nitrogen cooled, louvered shrouds, the effective sticking coefficient may be significantly lower than that achieved on a bare cryosurface. Simulations are, therefore, performed with values of 0.2, 0.4, 0.6, 0.8, and 1.0 to study the sensitivity of the results to this unknown parameter. The DSMC–PIC computations employ a grid of 91 by 61 uniform, rectangular cells. At steady state, the computations typically employ 200,000 particles and the total run time for each case is on the order of 4 h.

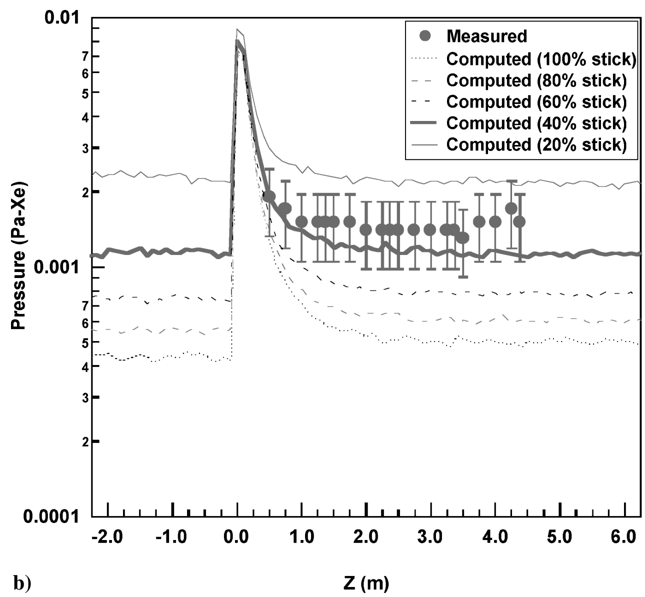
Results and Discussion

The results are presented for several cold-flow conditions of the Hall thruster in which the plasma is not ignited. These flows, therefore, simply consist of neutral xenon atoms, which will yield comparable backpressures for future pressure maps with the V1 in hot-flow mode.

The simulation results are compared directly with experimental measurements of pressure for a number of conditions in which the mass flow rate and pumping speed are varied. The highest values of the pressure map data in Figs. 4 and 5 are one order of magnitude below the upper limit of the BA ionization gauge. This is because the IGPS is positioned to allow the BA gauge to reach its upper limit



a)



b)

Fig. 5 Comparisons of simulated and measured pressure distribution within the LVTF for cold-flow operation of the NASA-173Mv1 Hall thruster a) at 10.46 mg/s and 140,000 l/s and b) at 5.25 mg/s flow rate and 140,000 l/s.

of 10^{-2} Pa (10^{-4} torr), 0.5 m downstream of the thruster exit plane for an anode mass flowrate of 14.09 mg/s.

Simulation results are presented in Fig. 4 for a mass flow rate of 10.46 mg/s and a total pumping speed of 240,000 l/s (all seven pumps operating). Both the experiment and simulation include flow of xenon through the cathode of 0.92 mg/s to mimic hot-flow operation. Figure 4 shows the data comparison along the thruster centerline for the five different values of the sticking coefficient. Clearly, very good agreement is obtained between the simulations and the measurements. Note that the ion gauges cannot be used within 50 cm of the thruster. The simulation results are sensitive to the sticking coefficient, although the profiles obtained with a value of 0.4 shows acceptable agreement with the measured data.

To investigate the generality of the performance of the simulations, two additional cases are simulated. The first retains the flow rate of 10.46 mg/s and considers the lower pumping rate of 140,000 l/s by turning off the three side pumps in the simulation. These results are shown in Fig. 5a. In Fig. 5b, the results are shown for a flow rate of 5.25 mg/s (again with 0.92 mg/s flowing through the cathode) with a total pumping of 140,000 l/s. In both Figs. 5a and 5b, acceptable agreement is obtained between simulation and experiment for a sticking coefficient of approximately 0.4.

The cryosurface sticking coefficient is a function of the cryosurface wall properties, the species of the particle colliding with the surface, and the energy of the colliding particle. There is a concern that the sticking coefficient varies significantly with the composition and thickness of the ice formation on the cryosurface rendering the sticking coefficient predictions useless. The two most prevalent issues are the thickness of the initial water–ice layer created from the facility humidity level and the thickness of the xenon–ice layer on the cryosurface. An LN_2 (70 K) flow through the cryopump shroud precedes the activation of the cryopump compressors. The LN_2-chilled shroud is the first surface inside the vacuum chamber to decrease to 273 K and remains the coldest surface for nearly 2 h. A large percentage of the water present in the vacuum chamber, after the mechanical pumps stop, freezes to the LN_2 shroud because the majority of the water molecules make at least one collision with the shroud before reaching the cryosurface. Therefore, the sticking coefficient, which is a function of the composition of the initial layer of ice on the cryosurface, is not significantly affected by the relative humidity in the facility at the time of evacuation.

Past data show that once a thin xenon–ice surface is present on the cryosurface that the pumping speed/sticking coefficient of the surface is nearly constant over a wide range of condensed xenon on the cryosurface.[21] For a xenon flow rate of 5.25 mg/s, the cryopumps within the LVTF reach this condition in approximately 5 min. Before collecting pressure map data in the LVTF, a 5.25-mg/s flow rate is condensed on the cryosurfaces for 30 min. Therefore, the sticking coefficient remains nearly constant for the duration of the pressure map experiment.

Relevant predictions about the hot flow may be made with the cold-flow data despite the large difference in temperature and velocity of the exit plane particles between the two conditions. The energy of the particle colliding with the cryosurface affects the sticking coefficient. The neutrals emanating from the hot anode and the high-speed ions created in the discharge chamber make at least one collision with the 300 K vacuum chamber wall before reaching the cryosurface. A particle collision with the wall accomplishes two things: 1) The vacuum chamber wall neutralizes the ion and 2) the inelastic wall collision absorbs energy transferred to the neutrals and ions in the discharge chamber. When the neutral particles reach the LN_2-chilled shroud surrounding the cryosurface, they are more similar in kinetic make up to the particles present in the cold-flow experiment than those at the thruster exit plane. Moreover, a large percentage of the particles will then strike the 70-K louvered LN_2 shroud before reaching the cryosurface. Thus, the particles that collide with the cryosurface are of nearly the same kinetic makeup for both the hot- and cold-flow experiments. This means that sticking coefficients determined during the cold-flow experiment should transport to simulations of the facility backpressure with the Hall thruster in operation.

Conclusions

The goal of this work is to create a numerical model and a technique for calibrating a vacuum chamber in terms of pressure to account for elevated back pressures while testing Hall thrusters. As a first step in this process, a neutral gas background pressure map of the LVTF is created at a series of cold anode flow rates corresponding to P5 Hall thruster operating conditions of 1.5, 3.0, and 9.0 kW. The experimental results are used to validate a numerical model of the LVTF with a cold-flow thruster. Although the simulation results are found to be sensitive to the sticking coefficient assumed for interaction between the xenon atoms and the cryogenic pumps, very good agreement is obtained between the simulation using values in the range of 0.3–0.4 and the measured data. These results form the foundation of our studies on the impact of vacuum facilities on Hall thruster test results.

Acknowledgments

The experimental research is supported by the Air Force Office of Scientific Research through Grants F49620-00-1-0201 and

F49620-01-1-0061. The modeling work is supported by the Air Force Research Laboratory and the Air Force Office of Scientific Research through Grant F49620-03-1-0123. In addition, Mitchell Walker is supported by the Michigan Space Grant Consortium and the National Science Foundation. The NASA-173Mv1 was developed jointly with NASA, John H. Glenn Research Center at Lewis Field through Grant NAG3-2307. We would like to thank Robert Jankvosky at NASA John H. Glenn Research Center for his assistance in calibrating the ionization gauges and loaning a hollow cathode and undergraduate Robert Thomas for his help constructing the ionization gauge positioning system and experimental setup.

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