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The USAF has identified high-power Electric Propulsion (EP) as an enabling technology for orbital transfer vehicles and re-supply ships. While the path for developing high-power EP systems is somewhat certain given NASA's recent success with its 70+ kW NASA-457M Hall thruster, it is clear that testing 50-kW-class thrusters in current test facilities is of concern given the high facility pressures. In response to this issue, the USAF has embarked on the concept of clustering the use of multiple Hall thrusters in a propulsion array-to allow a single thruster to be ground-tested on behalf of the entire cluster. While clustering is a logical approach to high-power EP, there is no fundamental understanding of how clustered thrusters operate or how one can use single-engine ground-based data to predict the performance, life, or interaction among engines, and the potential spacecraft integration issues associated with clustering. Our program addresses these issues by characterizing the influence of tank pressure on performance and plume characteristics for monolithic and clustered thrusters. We report on our second year studies on clustering, about how chamber pressure influences ion current density distribution, and summarize findings from cold- and hot-flow pressure map data of our vacuum chamber for a number of Hall thruster mass flow rates.

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Progress Report Submitted to Dr. Mitat Birkan of the AFOSR on

A Comprehensive Investigation of Facility Effects on the Testing of High-Power Monolithic and Clustered Hall Thruster Systems

AFOSR Grant - F49620-02-1-0051

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Abstract

The USAF has identified high-power Electric Propulsion (EP) as an enabling technology for orbital transfer vehicles and re-supply ships. While the path for developing high-power EP systems is somewhat certain given NASA's recent success with its 70^{+} kW NASA-457M Hall thruster, it is clear that testing 50-kW-class thrusters in current test facilities is of concern given the high facility pressures. In response to this issue, the USAF has embarked on the concept of clustering—the use of multiple Hall thrusters in a propulsion array—to allow a single thruster to be ground-tested on behalf of the entire cluster. While clustering is a logical approach to high-power EP, there is no fundamental understanding of how clustered thrusters operate or how one can use single-engine ground-based data to predict the performance, life, or interaction among engines, and the potential spacecraft integration issues associated with clustering. Our program addresses these issues by characterizing the influence of tank pressure on performance and plume characteristics for monolithic and clustered thrusters. We report on our third year studies on clustering, about how chamber pressure influences ion current density distribution, and summarize findings from cold- and hot-flow pressure map data of our vacuum chamber for a number of Hall thruster mass flow rates.

Introduction

Over the past year, the Plasmadynamics and Electric Propulsion Laboratory (PEPL) has conducted a wide array of electric propulsion research activities that were sponsored by the AFOSR and the Air Force Research Laboratory (Edwards). A brief summary of our Air Force sponsored work includes:

⇒ We are conducting proof-of-concept tests of TWSLIF by preparing an experiment that utilizes a commercial ion source to sputter a BN substrate. We have developed a technique for sending two laser wavelengths (one beam from a ring-dye laser and the other from a tunable diode laser) through the same optical train to the identical interrogation zone.

⇒ We completed a comprehensive plume characterization of the 2x2 BHT-200 Hall cluster both in PEPL's Large Vacuum Test Facility (LVTF) and AFRL's (Edwards) Chamber 6 that resulted in Dr. Brian Beal's (currently at Aerojet) doctoral thesis.[1] This characterization, which was done on both the cluster and a single BHT-200, included the use of:
  - ⇒ Hall probes to map the magnetic field;
  - ⇒ triple probes to measure electron temperature and number density;
  - ⇒ emissive probes to map the plasma potential;
  - ⇒ both an retarding potential energy analyzer (RPA) and a parallel-plate electrostatic energy analyzer (ESA) to measure the ion energy distribution; and
  - ⇒ gridded and nude Faraday cups to measure ion current density.

⇒ We are conducting a comprehensive performance and plume characterization study of the twin P5 Hall cluster that was shipped to PEPL from AFRL (Edwards) in 2002. This cluster was tested on the new, high-power null-type thrust stand built to support the P5 Hall cluster work. The null-type stand is identical to the one used by NASA to make performance measurements of the 70^{+} kW NASA-457. The "null" movement allows cluster performance to be made simultaneously with plume measurements. We presented the results of this effort this July at the 2004 Joint Propulsion Conference in Fort Lauderdale, Florida.[2]

⇒ The *TOPAZ* "tophat" energy analyzer has been built and calibrated at Michigan's Space Physics Research Laboratory (SPRL). This joint USAF-NASA sensor employs the state-of-the-art ion detection method used by instruments on deep-space missions. *TOPAZ* is the most advanced ion energy analyzer ever developed for electric propulsion research. *TOPAZ* will be used to characterize the plume of the P5 Hall cluster this fall. We presented the results of this effort this July at the 2004 Joint Propulsion Conference in Fort Lauderdale, Florida.[3]

⇒ We received the BUSEK 2x2 BHT-600 Hall cluster. Testing of the Hall cluster will commence in the fall.

⇒ We developed and tested a magnetically-filtered Faraday probe for making ion current density measurements in high backpressure vacuum chambers. The filter employs magnetic fields to remove low-energy Charge-Exchange ions from the Faraday probe collector. We presented the results of this effort this July at the 2004 Joint Propulsion Conference in Fort Lauderdale, Florida.[4]

Research Highlights

Hall Clusters – 2x1 P5

The University of Michigan and United States Air Force Research Laboratory have jointly created a cluster composed of two P5 Hall effect thrusters. The P5 is a 5 kW class laboratory model Hall thruster developed to investigate a thruster similar to that specified by Integrated High Payoff Rocket Propulsion Technology (IHPRT) goals. In this study, the performance characteristics of each of the P5 Hall thrusters are measured in the Large Vacuum Test Facility (LVTF) at the University of Michigan at three facility pumping speeds: 70,000, 140,000, and 240,000 l/s (xenon). The thrusters are evaluated over the range of 300 - 600 V at 5.25 mg/s and 10.46 mg/s. The two thrusters are then operated simultaneously and the thrust of the cluster is measured over the same thruster operating conditions.

Analysis of the monolithic thrust measurements shows that as the facility backpressure increases, the thruster discharge current and thrust increase because more background xenon gas is ingested into the thruster discharge chamber. The percent difference between the measured cluster thrust and the sum of the thrust measured for each monolithic thruster for the 10.46 mg/s anode flow rate varies from 11% to 16% as the operating pressure varies from 5.3×10^{-6} to 2.8×10^{-5} Torr. This is greater than the percent difference in thrust for the 5.25 mg/s flow rate, which varies from 0% to 6% as the operating pressure varies from $3.5x10^{-6}$ to $1.5x10^{-5}$ Torr. The abovementioned difference is caused by the ingestion of background gas and thus, the difference in thrust decreases as the cluster operating pressure decreases. In addition, the anode efficiency and specific impulse of the cluster is greater than that of a single monolithic thruster. Comparison of the performance characteristics of the cluster and the monolithic thruster for conditions of nearly equal operating pressure shows that for the 5.25 mg/s anode flow rate, the cluster thrust is simply the addition of the two monolithic thrusters. In addition, the anode efficiency and specific impulse are approximately equal to that of the monolithic thruster. These trends do not hold at the 10.46 mg/s anode flow rate for conditions of equal operating pressure because each cluster element elevates the operating pressure in the immediate vicinity of the adjacent thruster.

Hall Clusters – 2x2 BHT-200

An extensive array of plume data was obtained using a variety of plasma diagnostics including the triple Langmuir probe, floating emissive probe, Faraday cup, and retarding potential analyzer, as well as several others. Measurements were taken downstream of the 2x2 BHT Hall cluster, each element of which was coupled to its own hollow cathode and operated from its own set of power supplies. Data obtained in this nominal configuration were compared to parameters recorded in the plume of a single thruster. It was found that three of the most basic properties in the cluster plume: plasma density, electron temperature, and plasma potential, could be predicted based solely on knowledge of the characteristics of a single thruster and the geometric location of each device in the array. Predictions made using the methods presented in this dissertation appear to be accurate to within the margin of error of typical plasma diagnostics.

Secondary properties such as the ion current density and ion energy spectrum were also studied in the cluster plume. It was found that the beam profile of a cluster is slightly narrower than predicted by linear superposition of the contributions from each individual engine. A particle tracking algorithm revealed this behavior to be the result of low-energy ions being preferentially deflected downstream due to the unique plasma potential profiles in the cluster plume. Measurements of the ion energy spectrum showed a significant increase in ions at energy to charge ratios below the main peak in the distribution when multiple thrusters were operated. This appears to indicate an increase in elastic scattering due to clustering.

Finally, several alternative cluster configurations have been studied to examine parallel and shared cathode operation. It was found that parallel operation generally caused one cathode to dominate the discharge thus introducing a new criterion that must be considered when designing a cluster intended for parallel operation. When multiple thrusters were coupled to a single cathode, the plume properties could no longer be predicted using simple analytical formulas. This is because the operating characteristics of a single thruster depended on the location of the hollow cathode. The dramatic changes in plume properties observed in this configuration are the result of poor cathode coupling caused by operation with a distant cathode.

Magnetically-Filtered Faraday probe

The ability of a magnetically-filtered Faraday probe (MFFP) to obtain the ion current density profile of a Hall thruster is investigated. The MFFP is designed to eliminate the collection of low-energy, charge-exchange (CEX) ions by using a variable magnetic field as an ion filter. In this study, a MFFP, boxed Faraday probe (BFP), and nude Faraday probe are used to measure the ion current density profile of a 5 kW Hall thruster operated over the range of 300-500 V and 5-10 mg/s. The probes are evaluated in the University of Michigan Large Vacuum Test Facility at operating pressures within the range of 3.3×10^{-6} Torr to 8.4×10^{-6} Torr on xenon in order to study the ability of the Faraday probe designs to filter out CEX ions. Detailed examination of the results shows that the nude probe measures a greater ion current density profile than both the MFFP and BFP over the range of angular positions investigated for each operating condition. Because all other parameters are identical, the differences between the current density profiles obtained by each probe are attributed to the ion filtering systems employed. Analysis of the results shows that the MFFP provides the best agreement with flight-test data and between operating pressures.

TOPAZ

The design, development, and testing of the Top Hat Electric Propulsion Plume Analyzer (*TOPAZ*) for high-powered Hall thruster far-field plume diagnostics was finalized over this reporting period. *TOPAZ* incorporates a 'tophat' design with an analyzer constant of 100 resulting in a wide energy range and a high energy resolution. SIMION, an ion trajectory analysis program, is used to predict characteristics of the analyzer. An ion beam accelerator system confirms the computational results. *TOPAZ* provides an energy resolution of 2%, field-of-view of 107° by 26° (azimuthal by elevation) with an angular resolution in each direction of 2°, and a demonstrated energy-per-charge acceptance range of 5 eV – 15 keV.

Patent
LINEAR GRIDLESS ION THRUSTER, A. D. Gallimore and B. Beal,
U.S. Patent No. 6,640,535,
*I*ssued: Nov. 4, 2003

Awards & Honors
OUTSTANDING ACHIEVEMENT IN ACADEMIA, National GEM Consortium, 2004

Industrial Transfer

PEPL assisted the BUSEK Company in making plume measurements of their BHT-200 Hall thruster (see letter below). We transferred the design, software, and operating procedures for making RPA measurements in Hall thruster plumes.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Journal Publications (Air Force Sponsored Only)

1. King, L. B., and Gallimore, A. D., "Ion Energy Diagnostics in the Plume of an SPT-100 from Thrust Axis to Backflow Region," Journal of Propulsion and Power (AIAA), [Invited Article], Vol. 20, No. 2, March-April 2004, 193-203.

2. Walker, M. L, Gallimore, A. D., Boyd, I. D., and Chunpei, C. "Vacuum Chamber Pressure Map of a Hall Thruster Cold Flow Expansion," Journal of Propulsion and Power (AIAA), in press, 2004.

3. Beal, B. E., Gallimore, A. D., Haas, J. M., and Hargus, W. A., "Plasma Properties in the Plume of a Hall Thruster Cluster," Journal of Propulsion and Power (AIAA), accepted, 2004.

4. Walker, M. L, Victor, A., Hofer, R. R., and Gallimore, A. D., "Effect of Backpressure on Measured Ion Current Density Profiles of Hall Thruster Plumes," Journal of Propulsion and Power, accepted, 2004.

5. Keidar, M., Gallimore, A. D., and Raitses, Y. E., "On the Potential Distribution in Hall Thrusters," Journal of Physics Letters, accepted, 2004.

6. Walker, M. L, and Gallimore, A. D., "Neutral Density Map of Hall Thruster Plume Expansion in a Vacuum Chamber," Review of Scientific Instruments, 2004.

7. Walker, M. L, Hofer, R. R., and Gallimore, A. D., "Effects of Faraday Probe Design and Backpressure on Ion Collection in Hall Thruster Plumes," Journal of Propulsion and Power, 2004.

Conference Papers (Air Force Sponsored Only)

8. Rovey, J. L., and Gallimore, A. D., "Evaluation of a Magnetically Filtered Faraday Probe For Measuring The Ion Current Density Profile of a Hall Thruster, AIAA-2004-3948, 40^h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004

9. Smith, T. B., Herman, D. A., and Gallimore, A. D., Williams, G. J., "Laser-induced Fluorescence Velocimetry of Xe II in the 30-cm NSTAR-type Ion Engine Plume" AIAA-2004-3767, 40^h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004.

10. Walker, M. L. R., and Gallimore, A. D., "Performance Characteristics of a Cluster of 5 kW Laboratory Hall Thrusters," AIAA-2004-3767, 40^h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004.

11. Victor, A. L., Zurbuchen, T. H., Gallimore, A. D., "Development of the Top Hat

Electric Propulsion Plume Analyzer (TOPAZ)," AIAA-2004-4099, 40h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004.

References

[1] Beal, B. E. Thesis Title — "Clustering of Hall Effect Thruster for High-Power Electric Propulsion," Jan., 2004. *Now Researcher & Development Specialist at Aerojet's Electric Propulsion Center in Redmond, WA.*

[2] Walker, M. L. R., and Gallimore, A. D., "Performance Characteristics of a Cluster of 5 kW Laboratory Hall Thrusters," AIAA-2004-3767, 40h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004.

[3] Victor, A. L., Zurbuchen, T. H., Gallimore, A. D., "Development of the Top Hat Electric Propulsion Plume Analyzer (TOPAZ)," AIAA-2004-4099, 40h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004.

[4] Rovey, J. L., and Gallimore, A. D., "Evaluation of a Magnetically Filtered Faraday Probe For Measuring The Ion Current Density Profile of a Hall Thruster, AIAA-2004-3948, 40h AIAA/ASME/SAE/ASEE Joint Propulsion, Fort Lauderdale, FL, July 2004