AIAA SciTech Forum
8-12 January 2024, Orlando, FL
AIAA SCITECH 2024 Forum

10.2514/6.2024-1956

Demonstration of a 3D Printed Azimuthal Gas Diffuser for Hall Thrusters

Avery Clowes*
Olin College of Engineering, Needham, MA 02492

Albert Countryman†
Brandeis University, Waltham, MA 02453

Braden Oh‡, Christopher Lee§
Olin College of Engineering, Needham, MA 02492

An azimuthal-injection gas diffuser containing internal geometries impossible to manufacture using conventional subtractive techniques was designed and 3D printed with Somos PerFORM, a stereolithographic composite resin. A prototype of the diffuser was successfully used in short-term (< 2 hours) ignition tests of a Hall thruster operating at a peak power of 200W and thermal stress-related damage was observed. A second prototype with improved thermal behavior and discharge uniformity was used in a test that peaked at 628W and minor discoloration was observed. Material tests were done to characterize thermal expansion and percent weight loss up to 900° C and 1000° C, respectively. Results support the suitability of PerFORM to be used for fabricating short-lifetime thruster components.

I. Introduction

In recent years, additive manufacturing has changed the landscape of small-batch component manufacturing. For a relatively low cost, researchers and engineers can create parts with a wide variety of material properties and with geometries impossible to make using conventional techniques. The electric propulsion community has recently begun experimenting with 3D printing to create components such as ion thruster acceleration grids [1]. 3D printing has the potential to make electric propulsion research more accessible to under-resourced teams by unlocking paths towards rapid, low-cost prototyping. However, thruster components typically experience extreme temperature gradients, ultrahigh vacuum, and strong electromagnetic fields. To allow the use of 3D printing for fabrication of thruster components, the printed materials must be able to withstand such conditions.

As a proof-of-concept demonstration, a team of undergraduate students designed and built a Hall-effect thruster that included a 3D printed propellant diffuser to inject gaseous propellant azimuthally into the thruster channel [2]. The internal geometry of the diffuser was impossible to manufacture using conventional subtractive techniques. This paper reports on the design of the 3D printed diffuser, the results of live-fire testing on two manufactured prototypes, and the results of followup material analyses.

II. Hall Thruster Propellant Diffuser Design

A key driver of Hall thruster efficiency is the fraction of neutral propellant particles which are ionized; higher ionization fractions correspond to higher propellant utilization and therefore higher overall thruster efficiency. The ionization fraction is driven by the ionization mean free path of the neutrals in the thruster channel, λ, which may be calculated in the following manner [3]:

$$\lambda = \frac{v_n}{n_e \langle \sigma_i v_e \rangle} \tag{1}$$

where v_n is the axial velocity of a neutral propellant atom, n_e is the channel electron number density, and $\langle \sigma_i v_e \rangle$ represents the ionization cross section of the propellant. Hall thruster channel lengths are designed to be significantly

*Student Manager, Olin Plasma Engineering Lab.
†Student Researcher, Olin Plasma Engineering Lab
‡Founder, Olin Plasma Engineering Lab; AIAA Student Member.
§Professor of Mechanical Engineering.

longer than the mean free path in order to yield high ionization rates. Unfortunately, increasing the channel length of a thruster also increases energetic losses due to particle-wall collisions. Thus, it is advantageous to increase the ionization fraction of a thruster by reducing the neutral ionization mean free path, rather than increasing the channel length. Per Eq. 1, decreasing the axial velocity of neutrals will decrease the ionization mean free path, thereby increasing the ionization fraction at a constant channel length.

Many conventional Hall thrusters inject propellant axially [4–7], effectively maximizing the axial propellant velocity and thereby increasing the mean free path. Other existing thrusters inject propellant radially [8, 9], utilizing diffusers with complex geometries. Recent experiments with azimuthal injection [10, 11] have shown that azimuthal injection may increase both the ionization and anode efficiency of a Hall thruster operating with krypton propellant. However, the limitation of conventional manufacturing techniques restricted the geometry of the azimuthal injection channels used in those studies to be straight through holes. To bypass this geometric restriction, we designed a diffuser which dispenses propellant by means of a toroidal plenum with four branching helical channels, as shown in Fig. 1. The geometry of the diffuser prototype was constrained by minimum wall thicknesses and feature sizes required by the 3D printing process.

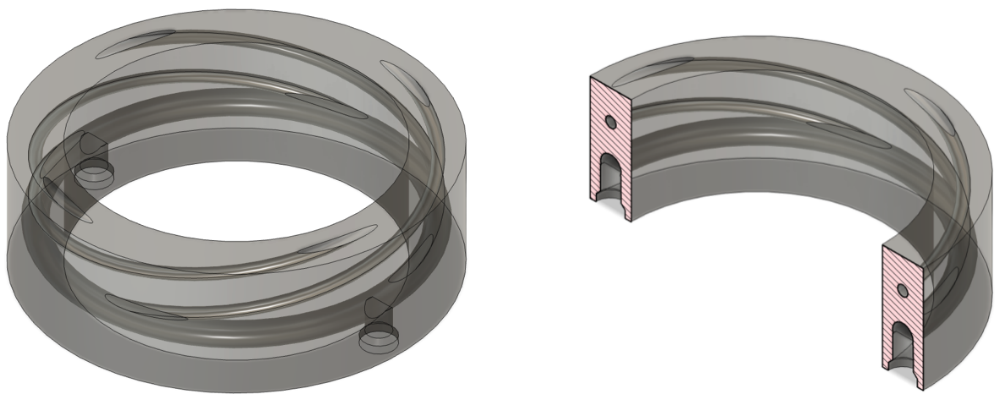

Fig. 1 CAD model and section view of the four-channel diffuser used during testing. This figure by Oh, et al. [2] is licensed under CC BY 4.0.

Initially, diffuser prototypes were planned to be made from three materials: Ceramic Resin V1 (Formlabs); Somos PerFORM (Statasys, Ltd.); and a laser-sintered aluminum (AlSi10Mg) alloy (Protolabs Inc.). The Formlabs Ceramic Resin consists of silica particles suspended within a liquid stereolithographic (SLA) resin. A part is first printed by using a traditional SLA process to harden the liquid resin into the part shape. The SLA-ceramic hybrid part is then baked in a kiln to burn out the resin and sinter the ceramic particles into a final component. Unfortunately, this prototype could not be successfully printed because the liquid resin had a tendency to clog the 3D printer valves.

A Somos PerFORM diffuser was successfully 3D printed (including thermal postcure) by a commercial vendor. The material is a high-stiffness, high-temperature-resistant, and high-dielectric strength composite resin. It is also known to survive high vacuum, as it has heritage as a material for CubeSat cold gas thrusters [12–14] and has been used to manufacture a mounting bracket for testing a small Hall thruster [15]. However, it was not known how the material would respond to the temperatures typically reached inside a Hall thruster channel. The PerFORM datasheet reports a deflection temperature under load of 268°C, but does not report a burn (or other maximum) temperature.

An additional prototype was manufactured from aluminum alloy using a direct metal laser sintering process by a commerical vendor. In the design of the thruster used for testing [2], the diffuser must also serve as an electrical standoff for the thruster anode, so it had to be electrically insulative. To create an insulative surface, the aluminum prototype was treated with sulfuric acid anodization to form a oxide layer on the surface. However, imperfections in the anodization left potentially conductive pathways through the diffuser, so this prototype was not used in live fire testing.

III. Ignition Testing Using the Four-Channel Diffuser

Ignition tests were conducted with a four-channel PerFORM diffuser integrated into a 50mm Hall thruster [2]. This thruster was ignited on February 1, 2023, and operated under a variety of conditions that spanned 100-200W of power at flows of 10-20 sccm of krypton propellant. A photo of the operational plasma is shown in Fig. 2. Distinct regions of brightness corresponding to the exit apertures of the diffuser are visible. These regions indicate non-uniform propellant distribution, as would be expected for a diffuser with only four outlet holes. Nevertheless, the diffusion was uniform enough for a steady thrust plume to be generated and sustained. The diffuser was used for approximately two cumulative hours of testing at a variety of power levels ranging from 100-200 W.

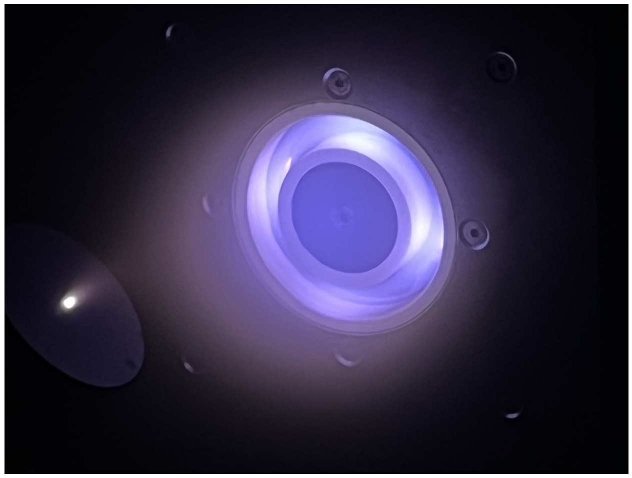

Fig. 2 Photograph of a krypton plasma formed during testing of the four-channel diffuser. Bright spots correspond to regions of high plasma density.

Following testing, the diffuser was removed from the thruster for inspection. Fig. 3 shows visible charring and fracturing on one half of the diffuser while the other half is distinctly clean. By visual inspection it is not apparent whether the fractures extended deep enough to penetrate into the helical diffusion channels.

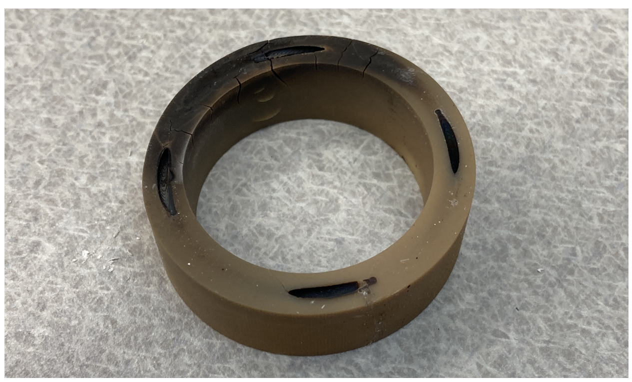

Fig. 3 Photograph of the four-channel diffuser post-firing.

We theorize that the charring and fracturing on only one side was the result of uneven heating caused by the charred side of the diffuser being in firm contact with the boron nitride channel wall. This occurred because the diffuser was misaligned within the thruster during assembly; if the diffuser were concentrically aligned with the channel, no contact would be made between the diffuser walls and channel walls. However, the diffuser was improperly aligned because a wire used to provide an electrical connection to the anode shifted the diffuser out of axial alignment. This can be seen in Fig. 4. Because boron nitride is thermally conductive and is in direct contact with the thruster plasma, it can reach very high temperatures. In the off-axis configuration shown in Fig. 4, the electrical wire unintentionally served as a thermal standoff that protected the un-charred side of the diffuser from contacting the channel wall while simultaneously pressing the charred side into a hot channel wall.

IV. Revised Diffuser Design & Ignition Testing

The successful ignition of a Hall thruster plasma with the four-channel diffuser validated the usage of a azimuthal diffuser geometry. To confirm the electrical wire standoff hypothesis and to reduce thermal damage, a revised version of

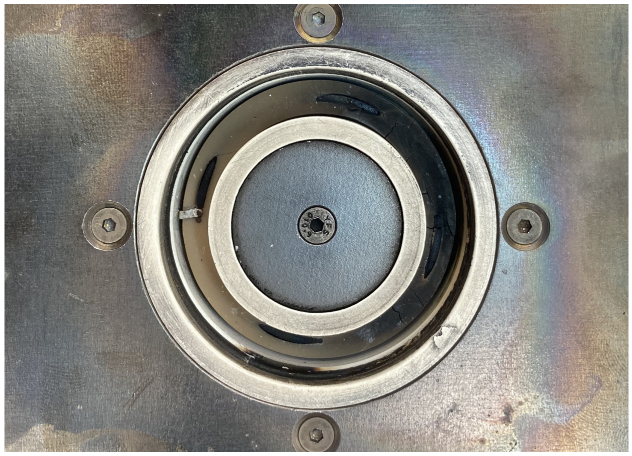

Fig. 4 Photograph of the thruster with the anode plate removed. Charring and thermal damage (right) is exactly opposite the side of the diffuser where a wire (left) is used to close the electrical connection to the anode.

the diffuser was constructed which contained three key design changes: 1) to reduce heat conduction to the diffuser from surrounding components, thin standoff ribs were added around the outer edge of the diffuser to reduce the available thermal conduction surface; 2) to further reduce the risk of thermal contact, the radial thickness of the diffuser was reduced; and 3) to produce a more even gas distribution throughout the thruster channel, the number of exit holes in the diffuser was increased from four to seventy. A CAD model of the revised design is shown in Fig. 5.

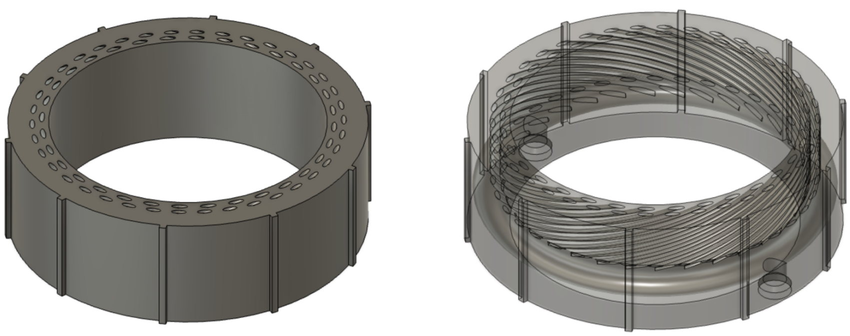

Fig. 5 Solid and transparent CAD models of the revised diffuser which has seventy holes, a reduced radial width, and ribs along the outside wall to reduce thermal conduction between the channel walls and diffuser body.

A second round of ignition testing was done to evaluate the new diffuser design in May 2023. These tests were also performed under a wider range of operating conditions. Steady-state plasma generation was achieved with both krypton and argon propellant across ranges of 10-30 sccm of flow and 100-628 W of power. An image of the plasma produced within the channel can be seen in Fig. 6.

The plasma produced during this set of experiments was substantially brighter and more evenly distributed throughout the channel because of the higher operational power achieved and the more even injection of propellant into the channel, respectively. The revised diffuser was in use for approximately one hour before being removed from the thruster for inspection which revealed significant surface discoloration but no stress fracturing, as shown in Fig. 7. A side by side comparison of the initial and revised diffusers is also shown in Fig. 8. The results of these tests demonstrates that PerFORM can serve as a rapid prototyping material for Hall thruster components undergoing short term testing at low power levels.

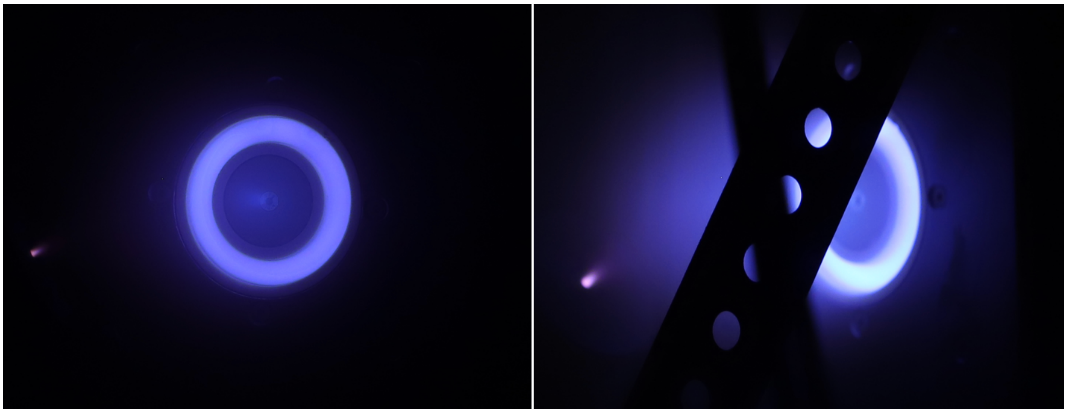

Fig. 6 Photographs from live-fire testing using the revised diffuser. The uniform glow of the plasma around the azimuth of the channel is a visual indicator of improved diffusion over the initial design used in Fig. 2.

Fig. 7 Photographs of the revised diffuser integrated into the Hall thruster following testing. The surface of the diffuser is visibly discolored, but no fractures were visible.

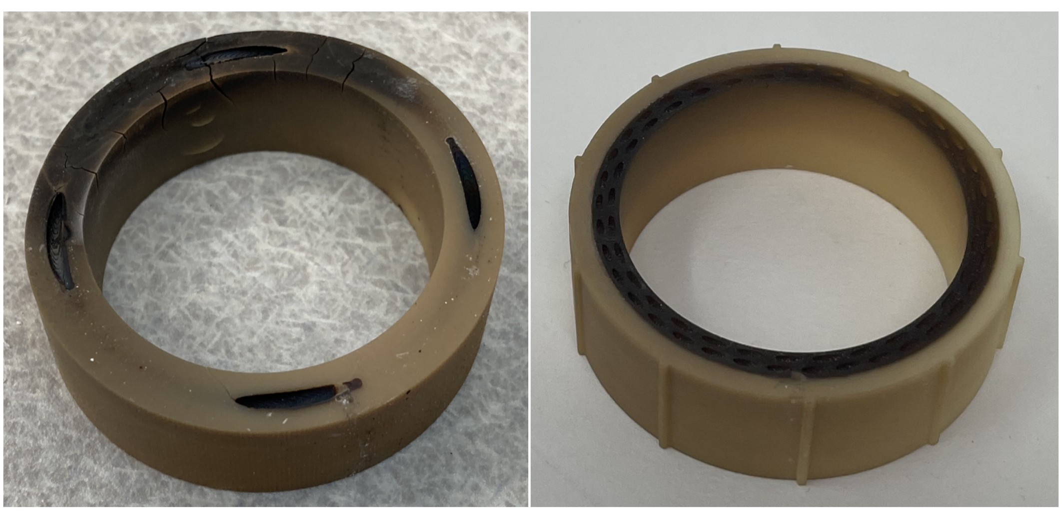

Fig. 8 Side by side photographs of the initial (left) and revised (right) diffusers, post-testing.

V. Material Thermal Testing

In order to better understand the thermal behavior and limits of the PerFORM material, thermogravimetric (TGA) and thermodilatometric (TDA) analyses were performed to characterize percent weight lost and thermal expansion over a range of temperatures. Both tests were conducted in an inert nitrogen environment. Testing was conducted on cubic samples (3.14 mm on a side) that were fabricated in the same method and by the same manufacturer as the four- and seventy-channel diffusers. For the (dynamic) TGA test, the temperature profile was set to an initial temperature of 300°C and then increased by 100°C every 45 minutes to 900°C. Fig. 9 shows a plot of the sample percent weight as a function of temperature.

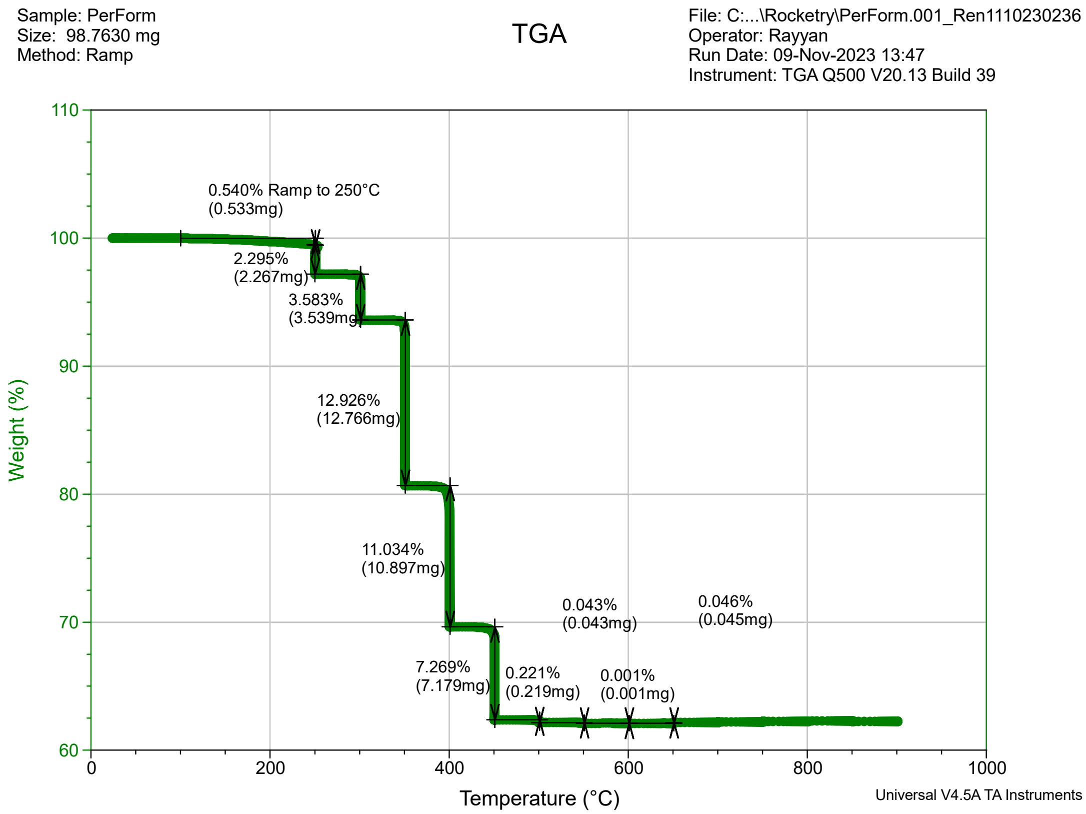

Fig. 9 Temperature vs. sample percent weight from TGA analysis of PerFORM material sample. At each step the percent mass loss is recorded. At 300°C, the weight lost is approximately 3.6%. Constant weight measured past 500°C corresponds to the conclusion of the bake-out process.

As shown by Fig. 9, at 300° C the sample lost approximately 3.6% of its initial weight. In the temperature range of 300-450° C, the percentage weight loss increases to approximately 37.9%. We theorize that this is due to degradation of the epoxy in PerFORM, as epoxy degradation within this temperature range is consistent with a TGA study performed by Yin and Zhang on a photocurable epoxy resin [16]. Beyond 500°C, there is little change in the weight of the sample, indicating that the remaining material is stable at high temperatures.

In addition to the TGA test, a TDA test was performed to characterize PerFORM's dimensional change for a temperature profile defined as follows: temperature was increased from ambient to 300 °C, held constant for 40 minutes, then increased from 300 °C to 1000 °C. Fig. 10 shows the temperature profile and the resulting dimensional change of the sample. The behavior of the material can be classified into three categories:

- **Bulk Response (0-300°C)** - A linear increase in dimension corresponding to a linear coefficient of thermal expansion(CTE). This CTE was calculated to be 81.2 μm/°C.
- **Bake Out (300-500°C)** - A steep decrease in dimension corresponds to the temperature range in which TGA shows the most significant mass loss.

- **Stable Response (500-1000°C)** - The change in dimension has a gradual negative slope. We theorize that this is due to silica particle sintering. Although the exact composition of PerFORM is proprietary, we note that the PerFORM material data safety sheet references a "treated nanosilica" component [17] and sintering of silica-based composites has been observed in this temperature range [18].

These results set bounds on the use of PerFORM as an engineering material. Both diffusers we tested were in direct contact with the Hall thruster anode. Although the temperature of the anode during these tests was unknown, the commercial BHT-200 (200W) and BHT-600 (600W) Hall thrusters have reported anode temperatures of ~ 370° C and ~ 300° C, respectively [19]. We note that these temperatures fall in the bake out range, implying that careful thermal management may be required to avoid significant mass loss when using PerFORM in Hall thrusters.

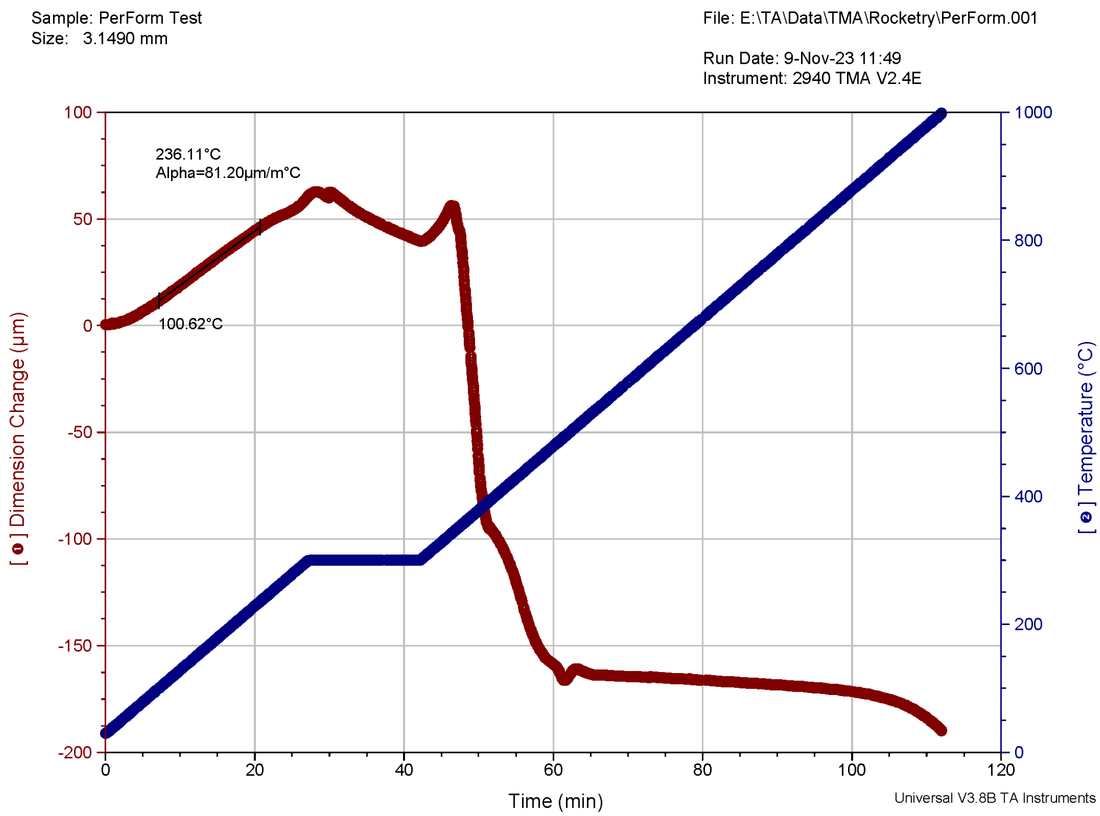

Fig. 10 Time vs. Temperature (blue) and Dimensional Change (red) from thermodilatometric analysis of PerFORM material sample. Linear CTE up to 300°C was calculated to be 81.2 μm/°C.

VI. Conclusion

This paper describes the design, fabrication, and successful testing of a novel azimuthal gas diffuser for Hall-effect thrusters. The diffuser design contains internal geometries that cannot be fabricated using conventional subtractive techniques. However, using additive manufacturing (3D printing), diffuser prototypes were readily created. Two prototypes, an initial four-channel design and a revised seventy-channel design, were used in successful ignition tests that ran for approximately two hours at a power level of 100-200 W, and for approximately one hour at a power level of 628 W (peak). No structural damage, *e.g.*, stress fractures, was detected by inspection of the revised diffuser after testing; although, significant surface discoloration was noted.

The diffusers were printed from Somos PerFORM, a commercially-available, high-thermal-resistance composite resin.The ignition demonstrations and follow-on thermal material tests show that PerFORM can safely withstand temperatures in the 0-300° C range, provided that the mechanical design can accommodate thermal expansion. Beyond

300° C, mass losses are observed, implying that careful thermal managements may be required when using PerFORM at temperatures typical to Hall thrusters [19]. This maximum temperature falls below that of other materials typically used for creating Hall thruster channels (*e.g.* boron nitride). However, the speed, flexibility, and cost of 3D printing may make this material worthwhile for rapid prototyping and design evaluation. This would be especially attractive to under-resourced (*e.g.*, student) teams.

These live-fire tests are a proof-of-concept that the proposed azimuthal diffusers as designed herein are viable for use in Hall-effect thrusters. The materials tests reveal that a more thermally stable material must be used to 3D print diffusers that will be run long term and/or at higher temperatures. Currently, this work is being extended to the design of a single-component propellant diffuser with fully-integrated thruster channel. An initial design has been 3D printed and preparations for testing are underway.

VII. Acknowledgements

The authors gratefully thank Prof. Oleg Batishchev of the Northeastern Plasma Physics Lab, Prof. Paulo Lozano of the MIT Space Propulsion Laboratory, and Prof. Alessandra Ferzoco and Matt J. Neal of Olin College of Engineering for providing the test facilities and instrumentation used to conduct this study. The authors also thank Prof. John Williams of Colorado State University and his team at Plasma Controls for providing the hollow cathode used to run the thruster. Funding for this work was provided by the Massachusetts Space Grant Consortium, Draper Laboratory, and the Babson College Foundry Fellowship Grant.

References

[1] Farnell, C. C., Thompson, S. J., and Williams, J. D., "Additive Manufacturing for Ion Optics," *Proceedings of the 37th International Electric Propulsion Conference. Cambridge. IEPC-2022-277*, 2022.

[2] Oh, B., Countryman, A., Regassa, M., Clowes, A., Miner, G., Kemp, S., McAneney, S. M., Klein, M., and Lee, C., "Design, fabrication, and testing of an undergraduate hall effect thruster," *Journal of Electric Propulsion*, Vol. 2, No. 1, 2023, p. 6.

[3] Goebel, D. M., and Katz, I., *Fundamentals of electric propulsion: ion and Hall thrusters*, John Wiley & Sons, 2008.

[4] King, L. B., Massey, D. R., Kieckhafer, A. W., and Makela, J. M., "A Vaporizing Liquid-Metal Anode for High-Power Hall Thrusters," Tech. rep., Michigan Technological University, 2007.

[5] Warner, N. Z., "Theoretical and Experimental Investigation of Hall Thruster Miniaturization," Ph.D. thesis, Massachusetts Institute of Technology, 2007.

[6] Baird, M., "Designing an Accessible Hall Effect Thruster," *Honors Theses*, Western Michigan University, Kalamazoo, MI, 2016.

[7] Wetherbee, J., Torres, D., Hering, S., Padilla, S., Gustavson, G., Korte-Wormley, K., Mokatish, O., Mhaske, S., Cruz, N., Ostrander, G., et al., "Student Design and Analysis of a Hall Effect Thruster," *AIAA SCITECH 2023 Forum*, 2023, p. 1598.

[8] Massey, D. R., King, L. B., and Makela, J., "Progress on the Development of a Direct Evaporation Bismuth Hall Thruster," *Proceedings of the 29th International Electric Propulsion Conference. Princeton. IEPC-2005-256*, 2005.

[9] Hruby, V., Szabo, J., Gasdaska, C., and Robin, M., "Hall thruster for use with a condensable propellant," U.S. Patent 9,334,855, May 2016.

[10] Xia, G., Li, H., Zhu, X., Ning, Z., Chen, S., Yu, D., and Zhou, C., "Effects of rotating supply mode on the ionization parameters of a krypton Hall thruster," *Vacuum*, Vol. 181, 2020, p. 109664.

[11] Xia, G., Li, H., Ding, Y., Wei, L., Chen, S., and Yu, D., "Performance optimization of a krypton Hall thruster with a rotating propellant supply," *Acta Astronautica*, Vol. 171, 2020, pp. 290–299.

[12] Imken, T. K., "Design and characterization of a printed spacecraft cold gas thruster for attitude control," Ph.D. thesis, 2014.

[13] Hart, S. T., Daniel, N. L., Hartigan, M. C., and Lightsey, E. G., "Design of the 3-D Printed Cold Gas Propulsion Systems for the VISORS Mission," *AAS GNC Conference, Breckenridge, CO, USA, AAS 22-095*, 2022.

[14] Hart, S. T., and Lightsey, E. G., "Improvements on Two-Phase Cold Gas Propulsion Systems for Small Spacecraft," *AAS GNC Conference, Breckenridge, CO, USA, AAS 23-174*, 2023.

[15] Bretti, M. A., “Progress and Developments of Ultra-Compact 10 Watt Class Adamantane Fueled Hall Thrusters for Picosatellites,” *Proceedings of the 37th International Electric Propulsion Conference. Cambridge. IEPC-2022-349*, 2022.

[16] Yin, B., and Zhang, J., “A novel photocurable modified epoxy resin for high heat resistance coatings,” *Colloid and Polymer Science*, Vol. 298, 2020, pp. 1303–1312.

[17] DSM Desotech Inc., “Safety Data Sheet, SOMOS PerForm,” `https://midwestproto.com/wp-content/uploads/2020/01/Somos-PerForm-DSM-Rev-10-2018.pdf`, 2018. Accessed: Dec 2, 2023.

[18] Chen, G.-h., and Liu, X.-y., “Low-temperature-sintering and characterization of glass-ceramic composites,” *Journal of Materials Science: Materials in Electronics*, Vol. 17, 2006, pp. 877–882.

[19] Matlock, T., Hargus, W., and Larson, C., “Thermographic Characterization and Comparison of 200W and 600W Hall Thrusters,” *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2007, p. 5241.