Initial Testing of a 3D Printed Gas Diffuser for Hall Effect Thrusters

Braden Oh*, James Jagielski†, Lily Dao‡, Ben Eisenbraun§, Avery Clowes¶, and Christopher Lee‖
Olin College of Engineering, Needham, MA, 02492

Albert Countryman**
Brandeis University, Waltham, MA, 02453

Christina Crochetiere††
Babson College, Babson Park, MA, 02457

The thrust of an electric propulsion engine is proportional to the number of ions ejected; ionizing higher percentages of propellant results in a higher thruster efficiency. Propellant ionization in a Hall thruster is optimized by reducing the mean free path of propellant particles. This can be achieved by reducing the axial velocity of the propellant. This team has designed and demonstrated a design for an azimuthal propellant diffuser that is unibody and cheap to additively manufacture. A diffuser was manufactured from Somos PerFORM and was tested in live-fire conditions. The diffuser successfully allowed the thruster to operate at steady state, though inspection of the diffuser post-firing showed evidence of uneven heating and cracking due to thermal stresses, indicating that greater thermal considerations must be made for future models of the diffuser.

I. Introduction

In the modern world, satellites are increasingly critical to advancing human progress. Satellites are a key technology for radio, television, GPS, and scientific measurements, such as weather monitoring and deep space science. They also power global knowledge-sharing and telecommunications capabilities of today, enabling us to monitor our natural world and be prepared to respond to challenges such as natural disasters and the effects of climate change. Another recent area of growth is satellite internet; although most internet infrastructure is currently established on Earth, satellite megaconstellations, such as those launched by OneWeb and SpaceX, are expanding the future of global communications.

In order to fulfill their roles, satellites must be placed in very specific orbits. Satellites are launched into orbit on combustion rockets that create high thrust for short periods of time. These rockets are very inefficient, however, so many modern satellites utilize electric propulsion once they reach orbit. Electric propulsion engines utilize electromagnetic fields to propel ions into space and can be five to ten times more efficient (per effective exhaust velocity) than liquid rockets [1]. Electric propulsion systems decrease the mass and volume cost required to operate satellites and are a major step being taken to improve space travel.

The Olin Plasma Engineering & Electric Propulsion (PEEP) Lab seeks to create opportunities for undergraduate engineering students across the United States to learn about and participate in developing new electric propulsion technologies. PEEP students have designed and built two Hall effect thrusters [2, 3], the latter of which contained a novel 3D printed propellant diffuser. In this paper, the team reports the initial results of testing this diffuser and outlines next steps for improving that integral component.

*Engineering Physics, class of 2023
†Electrical Engineering, class of 2025
‡Mechanical Engineering, class of 2026
§Mechanical Engineering, class of 2025
¶Mechanical Engineering, class of 2024
‖Professor of Mechanical Engineering
**Physics, class of 2024
††Business and Entrepreneurship, class of 2025

II. Hall Thruster Plasma Formation

In a Hall effect thruster, neutral propellant atoms are ionized via electron bombardment. This is achieved in the following manner:

1) The Hall thruster uses an axial electric field to draw electrons into the thruster channel. These electrons are often emitted by an external plasma source called a cathode.
2) A radial magnetic field traps the electrons as they enter the thruster channel; electrons experience a Lorentz force-enabled $E \times B$ drift which causes the electrons to move in a circular path. This azimuthal flow is the Hall current that gives the Hall thruster its name.
3) Neutral gas atoms injected from the bottom of the channel collide with this swirling cloud of high-energy electrons and become ionized (electron bombardment), creating the plasma.

The classical model for electron bombardment describes electrons which collide with propellant atoms, lose kinetic energy, slow down, and fall towards the anode, regaining kinetic energy as they fall through the electric potential (until they finally strike the anode). However, this classical description is incomplete as many more electrons fall through the magnetic field than would be expected in so-called "anomalous electron transport" [4], which is an open field of study.

Only ionized particles are accelerated by the thruster's electric field (and meaningfully contribute to the thrust), hence optimizing the number of propellant atoms (neutrals) ionized increases the efficiency of the whole thruster. The ionizing interactions between the neutrals and the trapped electrons are captured by the ionizing mean free path of the neutrals. This mean free path is the average distance a neutral atom travels before experiencing an ionizing collision with an electron and may be found by the following equation, provided by Goebel and Katz [5]:

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

where v_n is the axial velocity of a neutral propellant atom, n_e is the electron number density, and $\langle \sigma_i v_e \rangle$ is the experimentally-determined ionization cross section of the propellant, which quantifies the probability of ionization for a collision with an electron at a particular electron temperature. Goebel and Katz [5] further report that the relationship between plasma length and fraction of ionized neutrals is

$$L = -\lambda \ln(1 - p) \tag{2}$$

where p is the decimal fraction of neutrals that leave the thruster ionized. Rearranging Eqn. 2 yields the relationship

$$p = 1 - e^{-L/\lambda} \tag{3}$$

Therefore, for a thruster of a given plasma length, L, the percentage of propellant ionized is maximized by reducing the mean free path, λ. A mean free path variable that is easy to control is the axial velocity of the neutrals, v_n. Referring to Eqn. 1, when v_n is reduced, λ is reduced, and p is therefore increased.

An alternate way to conceptualize this relationship is that reducing the axial velocity increases the longevity, or lifetime, of the propellant within the channel. The longer a neutral lasts inside the channel, the higher the chance that it collides with a high-energy electron before escaping the thruster.

III. Diffuser Design

Given that injecting the propellant into the thruster channel with minimum axial velocity will maximize propellant ionization, a propellant diffuser can be designed accordingly: the team designed a diffuser that injects propellant azimuthally, instead of directly axially. Recent experiments from researchers at the Harbin Institute of Technology in China have confirmed that azimuthal injection reduces propellant axial velocity [6] and increases both the ionization and anode efficiencies of krypton propellant [6, 7].

Azimuthal injection was achieved by pushing propellant through two inlet holes into a toroidal plenum (to more evenly distribute the inlet pressure). Branching off of this plenum were four helical channels that guided the propellant into an azimuthal trajectory. A computer aided design (CAD) model of this diffuser geometry is shown in Fig. 1. The diffuser used in this experiment contained only four relatively large tubes because the team originally intended to manufacture the diffuser from a ceramic material that required particular sizes of interior features and wall thicknesses.

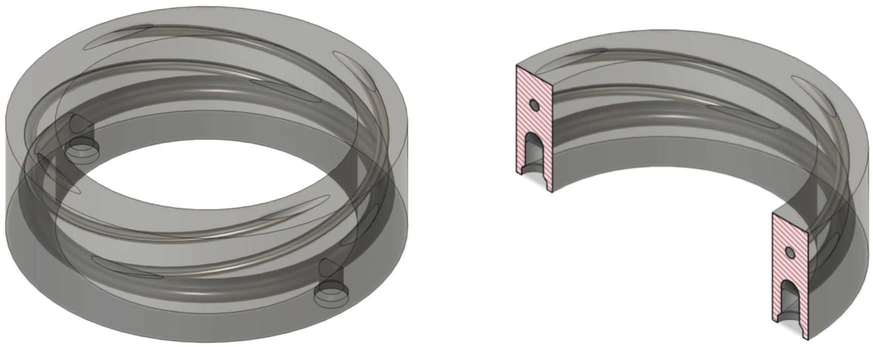

Fig. 1 CAD model and section view of the diffuser used during testing. This figure by Braden Oh, et al. [3] is licensed under CC BY 4.0.

The design for this diffuser necessitates additive manufacturing. The interior features that connect the toroidal plenum to the outlet ports are angled and curved in nature, making them impossible to manufacture with conventional machining techniques. This constraint made additive manufacturing necessary to achieve the design outlined in CAD. Three versions of the depicted diffuser were successfully prototyped: one from a low temperature stereolithographic (SLA) resin; one from a high temperature SLA resin called Somos PerFORM; and one from direct metal laser sintered (DMLS) AlSi10Mg aluminum alloy. The DMLS prototype was black anodized after printing to ensure the surface was electrically insulative. Images of these prototypes are shown in Fig. 2. A fourth prototype was attempted to be made from a Formlabs SLA resin with suspended ceramic particles (the part would be sintered post-printing to fuse the ceramic), but the resin repeatedly clogged the Formlabs printer's dispenser valves and prevented printing.

Fig. 2 The three types of prototyped diffusers. From left to right: low temperature SLA resin, Somos PerFORM, and black anodized aluminum. This figure by Braden Oh, et al. [3] is licensed under CC BY 4.0.

The diffuser made from PerFORM was of greatest interest to the team for two reasons. First, PerFORM is an inexpensive material that can be used for very rapid prototyping. Second, PerFORM has previous space propulsion heritage; PerFORM has previously been used to manufacture cold gas thrusters for CubeSats [8] (demonstrating an ability to run high-pressure propellant under vacuum), and to hold small Hall thrusters during ground testing [9] (demonstrating an ability to survive high temperatures under vacuum). Because it had not been used to directly manufacture a component within an electric propulsion engine, this experiment would serve as an initial demonstration.

PerFORM has a deflection temperature under load (DTUL) of 268°C. Flame and/or burning temperature data for PerFORM is not publicly available. Although 268°C is lower than temperatures typically experienced inside a Hall thruster, the design of the thruster used for testing placed the diffuser under no mechanical load, so it was expected that the true failure temperature of the part would be significantly higher.

IV. Live-Fire Testing

A PerFORM diffuser was integrated into a 50mm Hall thruster built by a team at Olin College in 2022[3]. The diffuser was seated at the bottom of the main boron nitride channel with its top surface directly contacting the steel anode. A thermocouple was inserted through a hole in the channel wall to contact the side of the diffuser. Two brass pipes fed krypton gas into the rear of the diffuser. An image of the assembled thruster is shown in Fig. 3.

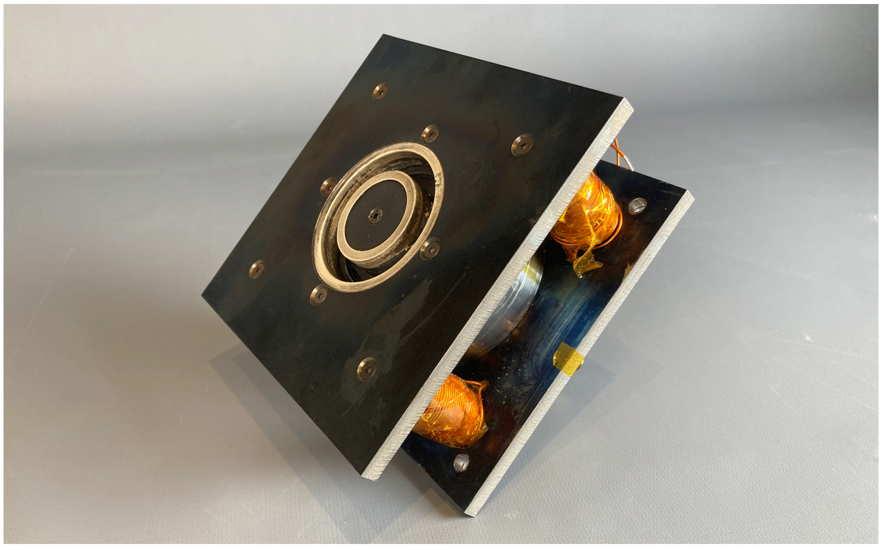

Fig. 3 A post-firing photograph of the thruster used to test the diffuser.

This thruster system was tested under live-fire conditions. During these tests the diffuser dispensed 10-20 SCCM of propellant at thruster power levels in the range of 100-200 W. Early on in the testing process an anomalous high voltage on the diffuser thermocouple lines caused the thermocouple amplifier chip to burn out. Out of concern for the safety of the operators, the thermocouple lines were disconnected and isolated and direct temperature data could not be taken.

The operational plasma showed distinct regions of brightness corresponding to the exit apertures of the diffuser, but the color became more uniform further away from the surface of the anode, as shown in Fig. 4. This gradient indicates highly unequal propellant distribution by the present design; nevertheless, the diffusion was uniform enough for a steady thrust plume to be generated and sustained.

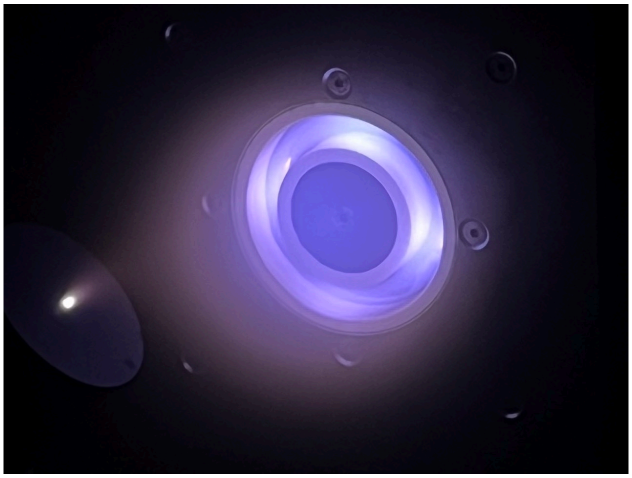

Fig. 4 Photograph of a krypton plasma formed during testing. Bright spots correspond to regions of high plasma density.

An additional phenomenon observed while testing the thruster was a rotating spoke instability[4] with a frequency of approximately 1 Hz that manifested at low magnetic field strengths. Four still frames extracted from video of this instability are shown in Fig. 5. The spoke instability's ability to travel all the way around the circumference of the channel is further evidence of the diffuser's successful operation.

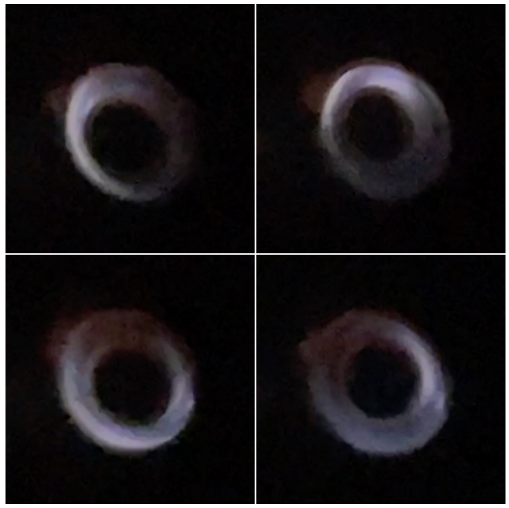

Fig. 5 Still frames from video of a clockwise-rotating spoke instability.

Following testing, the thruster was disassembled so that the diffuser could be inspected. As shown in Fig. 6, charring and fracturing was visible on one half of the diffuser while the other half was distinctly clean. It is not readily apparent whether the fractures, which are presumed to have been created by thermal stress, penetrated deeply enough to penetrate the diffusion pathways.

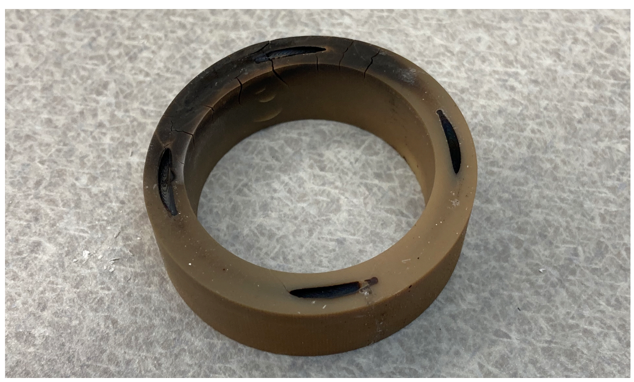

Fig. 6 Photograph of the diffuser post-firing.

The presence of charring and fracturing on only one side of the diffuser implies that thermal energy was either excessively accepted or unable to be rejected from that side alone. It is notable that the side of the diffuser that experienced charring was directly opposite the side which accommodated a wire used to close the anode electrical connection, as shown in Fig. 7.

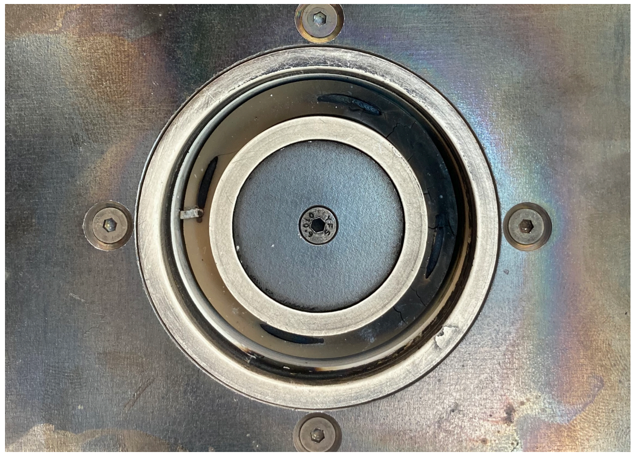

Fig. 7 Photograph of the thruster with the anode plate removed. Charring and thermal damage (right) is exactly opposite the side of the diffuser which accommodates a wire (left) used to close the electrical connection to the anode.

A possible explanation for this orientation of thermal damage is that the electrical wire pushed the diffuser off of its axial alignment and into the channel wall. The channel walls are made from thermally conductive boron nitride and contact the thruster plasma, and thus reach very high temperatures. As the electrical wire knocked the diffuser off-axis, it simultaneously pressed the charred side into the exterior channel wall and served as a thermal standoff between the 'clean' side of the diffuser and the channel wall. This excessive thermal conduction could have led to the failure observed. Additional experiments will be conducted to verify this hypothesis and search for a diffuser design that is robust to this failure mode.

V. Next Steps

This experiment demonstrates that although PerFORM can be used to 3D print a critical gas diffusion component inside of a Hall thruster, as a material it is susceptible to charring and thermal fracturing. To further study its applicability to Hall thruster components, three future experiments are being planned:

1) Validate the electrical wire hypothesis by live-fire testing a diffuser with modified geometry.
2) Identify the charring and thermal fracturing temperatures of PerFORM by baking blocks in a high-temp oven.
3) Determine the usable lifetime of PerFORM as a Hall thruster channel.

Experiment one will be to validate the electrical wire hypothesis for the charring observed. This will be achieved by manufacturing a diffuser with a narrower radial width than the one previously tested. The new diffuser will also have thin ribs on the outside surface to prevent high-surface-contact thermal conduction from occurring.

Experiment two will be to identify the exact failure temperature of PerFORM. This will be found by baking small 3D printed blocks in a furnace at increasingly high temperatures until charring and thermal fracturing is observed.

Experiment three will be to determine how long PerFORM can be used within a Hall thruster at high temperature. This will be achieved by 3D printing an entire thruster channel from PerFORM and observing how the material breaks down after various lengths of live fire time. The purpose of this test is to find out whether PerFORM can feasibly be used to prototype new designs for thruster components in a cheap and rapid way, prior to manufacturing out of a more delicate or expensive material.

VI. Conclusion

This initial experiment demonstrates that an azimuthal gas diffuser 3D printed out of PerFORM is indeed capable of delivering sufficient propellant flow to run a 100-200W Hall thruster at steady state for brief periods of time. However, PerFORM is susceptible to burning and cracking at very high temperatures, indicating that careful thermal management must be considered when using PerFORM to directly manufacture Hall thruster components. Future experiments are being planned to identify the exact temperatures and lengths of time for which components manufactured from PerFORM may be used within a Hall thruster without charring or fracturing.

Acknowledgments

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References

[1] Choueiri, E. Y., "New dawn for electric rockets," *Scientific American*, Vol. 300, No. 2, 2009, pp. 58–65.

[2] Oh, B. K., Kunimune, J. H., Spicher, J., Anfenson, L., and Christianson, R., "Undergraduate Demonstration of a Hall Effect Thruster: Self-Directed Learning in an Advanced Project Context," *2020 ASEE Virtual Annual Conference Content Access*, 2020.

[3] Oh, B., Countryman, A., Regassa, M., Clowes, A., Miner, G., Kemp, S., McAneney, S. 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.

[4] McDonald, M. S., "Electron Transport in Hall Thrusters," Ph.D. thesis, University of Michigan, Ann Arbor, MI, 2012.

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

[6] 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.

[7] 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.

[8] 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," *2022 AAS GNC Conference, Breckenridge, CO, USA*, 2022.

[9] 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.