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Monofilament Vaporization Propulsion (MVP) – CubeSat propulsion system with inert polymer propellant

Curtis Woodruff, David Carroll, Darren King, Rodney Burton, and Neil Hejmanowski
CUA, L.L.C.
Champaign, IL, 61820; (309)-255-8442
woodruff@cuaerospace.com

ABSTRACT

CUA has developed an electrothermal thruster which consumes an inert polymer propellant fiber. This technology retains performance characteristics competitive with other warm gas systems, but enables more accessibility to micropropulsion via dramatically reduced cost and the elimination of range safety concerns. CUA's Monofilament Vaporization Propulsion (MVP) draws from extrusion 3D printer technology to feed and melt polymer propellant in preparation for evaporation and heating up to 1100K using CUA's micro-resistojet technology. Despite undergoing depolymerization and two separate phase changes, the system power requirements are manageable, demonstrating typical specific thrusts of 0.16 mN/W, and a maximum specific impulse in excess of 100 s. 1U system performance exceeds 500 N-s total impulse.

INTRODUCTION

Propulsion systems for CubeSats are evolving with a wide variety of thrust, specific impulse, and power draw levels and corresponding trade-offs, but still very few have flown to date. A good summary of CubeSat propulsion systems through 2016 is provided by Lemmer [2017]. Monofilament Vaporization Propulsion (MVP) is an effort by CUA (Champaign-Urbana Aerospace) to increase availability and ease of launch for CubeSat propulsion. Liquid propellant systems with pressurized vessels and valving are costly, and may not be accepted by range safety. One potential option dating back to the earliest electric propulsion systems, the PPT, is not always applicable as the high specific impulse results in a low specific thrust, not to mention the inherently low electrical efficiency. MVP is an electrothermal system, rather than electromagnetic, using modified subsystems from extrusion based 3d printing to store and flow large quantities of polymer propellant in filament form. The propellant, polyoxymethylene (POM, tradename Delrin), has a high storage density of 1.4 g/cc (at demonstrated 89% packing factor when spooled). Furthermore, it is a low outgassing plastic already used in space applications. Current efforts aim to package the technology in a 1U propulsion system, providing greater than 500-N-s total impulse.

TECHNOLOGY DESCRIPTION

MVP development focused on four major subsystems: propellant storage, a mechanical feed system, temperature controlled extruder, and a micro-resistojet superheater. Propellant is stored on a spool, and fed with a mechanical feed into a temperature controlled extruder to melt the propellant. All of those subsystems are already available as COTS parts for 3d printers, and were utilized in development and testing. The evaporation and heating of the propellant had more inherent risk, as it is a new process. Figure 1: MVP block diagram **Figure 1** shows a system block diagram with the four major subsystems. Detailed descriptions will follow, going from "cold" to "hot".

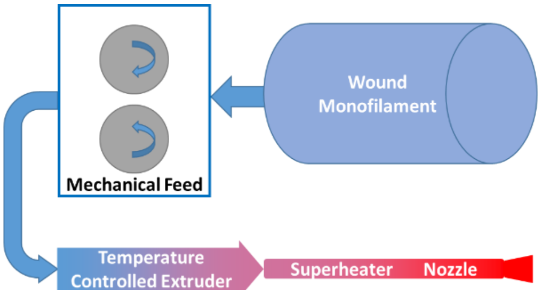

Figure 1: MVP block diagram

Feed and Storage

Proof of concept for the spooled propellant storage was completed early in the Phase I program. MVP utilizes a fixed spool, so that torques on the spacecraft are minimized. Propellant is unspooled in a manner similar to an open-faced fishing reel, although it is then drawn back through the spool core, where the rest of the subsystems are located. This is illustrated in **Figure 2**.

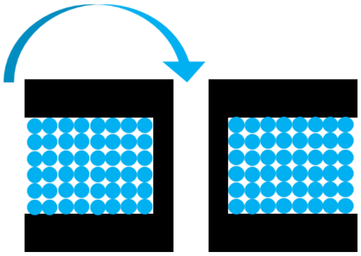

Figure 2: Spooled propellant

An experiment using a COTS 3d printer feed motor helped define internal tolerances for the 1U system. A propellant load was unspooled without tangles or binding, as shown in **Figure 3**. Obviously propellant tangled after leaving the unit, although in a real system it would have been melted and evaporated.

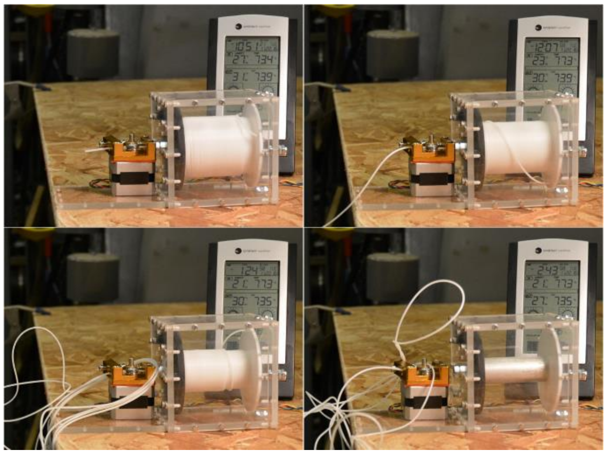

Figure 3: Propellant unspooling time-lapse

The motor will be located within the spool, which is most visible in the bottom right image of **Figure 3** (empty), and thrust is along the axis of the spool. In this case exhaust gases would be expelled from right to left. A COTS geared brushes motor with vacuum lubricant options fits within the core of the system, and drives the propellant with the same maximum available torque as the NEMA 17 3d printer motor used in **Figure 3**. The prototype flight-like feed system is shown in **Figure 4**. It has demonstrated successful propellant fiber feed and draws less than 0.5 W.

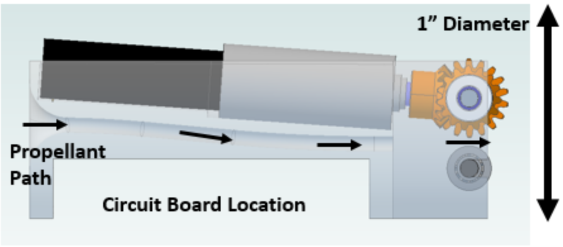

Figure 4: Prototype flight-like feed

Melt and Evaporation

Extrusion 3d printers use the mechanical feed to push propellant through a barrel into a heated nozzle. The barrel contains a thermal gradient wherein the propellant melts. After melting, a 3d printer uses a nozzle to dispense the melted polymer for printing, but MVP directly couples a resistively heated tube to further heat and evaporate the propellant. This "superheater" is based upon CUA's CHIPS micro-resistojet technology [Hejmanowski, 2015; Hejmanowski, 2016; Hejmanowski, 2018]. A diagram showing the transition is shown in **Figure 5**.

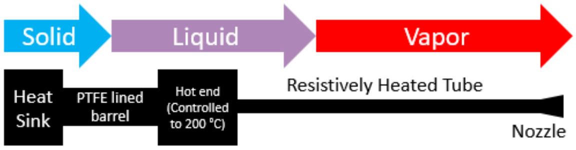

Figure 5: Phase transition in MVP

These components, along with the drive motor can be seen in the breadboard apparatus used for thrust stand testing, **Figure 6**.

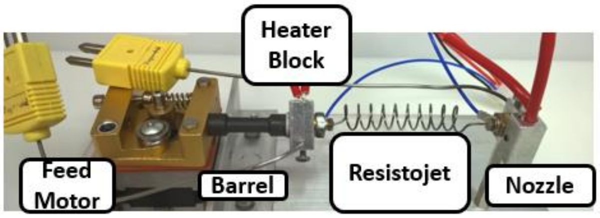

Figure 6: MVP breadboard

PERFORMANCE

The complete phase change from solid to gas requires roughly 2000 J/g, (sum of heat of fusion and evaporation enthalpy). As a result, flow rates are limited by available system power. Early data was taken at flow rates between 2 and 4 mg/s, and calculations suggest between 7 and 14 W of power is required for final gas temperatures approaching 1100K. This is before losses to radiation, conduction, and even convection from ambient pressure in the vacuum tank. During evaporation, the POM propellant breaks down into its monomer, formaldehyde, which has a molecular weight of 30 g/mol. At high temperatures and pressures, the formaldehyde will break down further, ultimately into hydrogen and carbon dioxide. Unfortunately, there are intermediate gas decomposition products that can produce solid carbon, which slowly builds up in the resistojet over the life of the thruster. In response, flow rates have been increased in excess of 8 mg/s, requiring a full 28W for this level of heating. This necessitates good shielding and isolation, as this power level is approaching the limit for smaller satellites. This higher flow operation, along with a high flow velocity in the tube, prevents buildup from accumulating too rapidly, allowing for a complete 1U propellant load before any signs of clogging.

Table 1 lists thrust stand results from various operational modes. Nozzle designs are not consistent across the presented data, but noted. The higher flow rate cases support the longest system life. All data is taken on the UIUC compact thrust stand [Hejmanowski, 2015]. Use of a radiation shield on the superheater is noted, as variations in the breadboard apparatus prevented the installation.

Table 1: MVP Thrust Stand Results

ṁ [mg/s]	Power [W]	Thrust [mN]	Isp [s]	Notes
2.8	20	2.9	104	Radiation shielded, 20° nz
3.2	27	3.4	107	Radiation shielded, 20° nz
3.8	40	3.7	100	Unshielded, 20° nz
8.2	40	6.7	83	Unshielded, 40° nz, supports system life

MODELING

The flow conditions supporting maximum system life, i.e. low pressure, high velocity, low tube residence time, are unfavorable for nozzle performance. Coupled with the larger throat sizes that enable these conditions, Reynolds numbers are lower than desired.

In order to advance the theoretical understanding of the performance of MVP and aid in design, CUA utilized its internally developed commercial BLAZE Multiphysics™ Simulation Suite [Palla, 2011] in order to construct high-fidelity simulations of the nozzle system component. BLAZE is comprised of a number of inter-operable and highly scalable parallel finite-volume models for the analysis of complex physical systems dependent upon laminar and turbulent fluid-dynamic (incompressible and compressible subsonic through hypersonic regimes), non-equilibrium gas- and plasma-dynamic, electrodynamic, thermal, and optical physics (radiation transport and wave optics).

Simulations of the nozzle which provided the highest performance in Phase I testing (first two entries in Table 1) indicated a larger than desired boundary layer that filled >30% of the nozzle, resulting in part from the low Reynolds number and high viscosity of the flow. The velocity profile of this nozzle is shown in **Figure 7**.

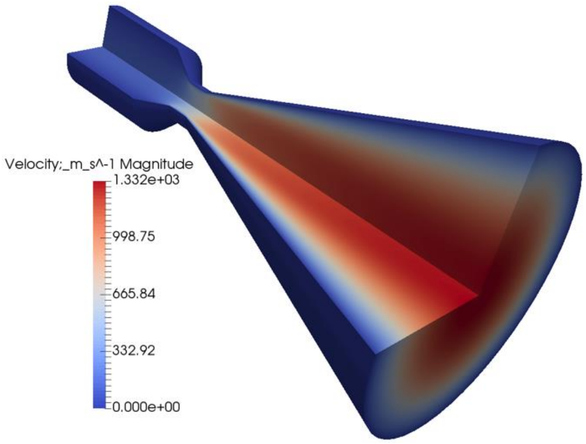

Figure 7: 2D-axisymmetric BLAZE results for 20° half-angle nozzle at 3 mg/s flow rate

A parametric sweep of nozzle half-angles was performed and suggests that for this particular application, unconventionally large half angles can increase performance, as shown in **Figure 8**. These results are consistent with findings of Williams and Osborn [2017] for nitrogen-fed micro-nozzles.

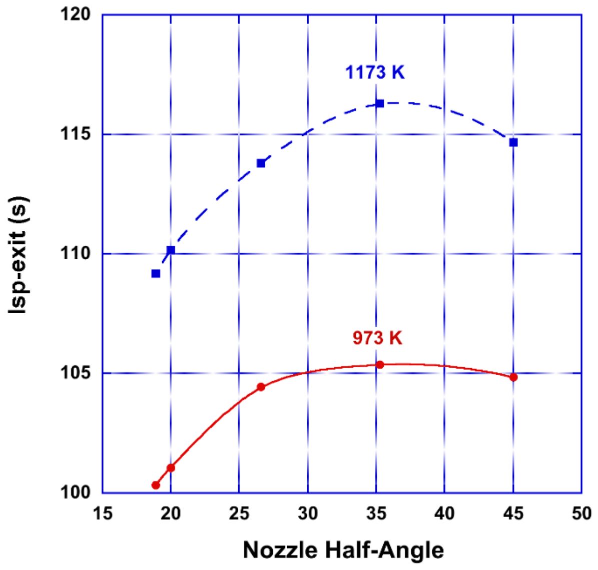

Figure 8: BLAZE predictions of nozzle exit Isp

With this in mind, the nozzle for the high flow case at the bottom of **Table 1** was designed with a higher half-angle. While the Reynolds number is almost matched, the flow is of lower temperature, and has some heavier molecules due to the lower specific power applied. The addition of shielding, along with higher vacuum should provide some additional performance, but with 83 s, system total impulse exceeds 500 N-s. **Figure 9** shows the simulated velocity profile of the larger half-angle nozzle. In particular, note that the 35° half-angle nozzle has a fraction of the nozzle filled by the boundary layer that is smaller than that shown in **Figure 7** for the 20° nozzle, thereby resulting in a higher Isp (**Figure 8**).

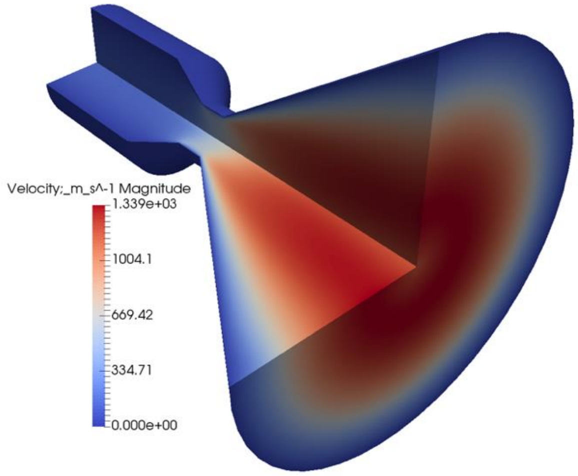

Figure 9: 2D-axisymmetric BLAZE simulation for 35° half-angle nozzle

INTEGRATED SYSTEM

Using the refined hardware models and the current thrust stand data, the MVP system specifications are presented below. While high quality radiation shielding reduced power required by a factor of 2 for the low flow rate cases, this level of effectiveness is not possible for the high flow case, since 28 W is required for the heating as discussed in the **Performance** section (above). Total system power is estimated to be 35 W, as the drive motor and supporting electronics consume around 1 W. The heater for melting (see **Figure 5**) is included in the 28 W budget, and ends up drawing enough waste heat from the superheater to remain off during operation. Flow rate and power can be reduced at a small performance penalty, but the conditions presenting are the best that currently support full system life. A render of the flight hardware is shown in **Figure 10**, and system performance parameters are shown in **Table 2**.

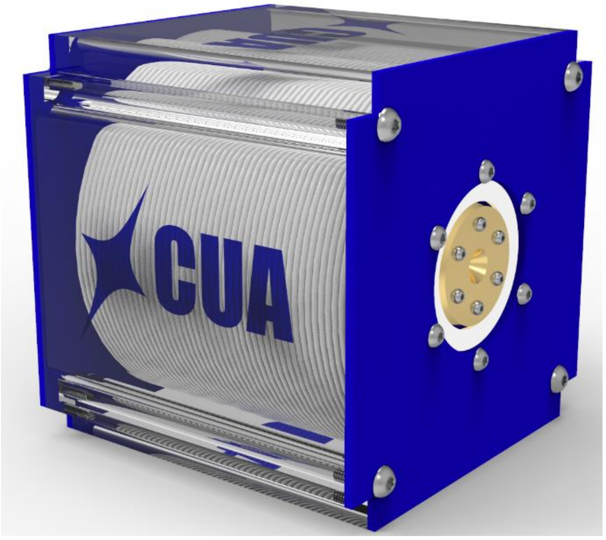

Figure 10: MVP Flight Unit Rendering

Wall construction will not be clear plastic, but this helps visualize the spooled propellant contained within the system. Some materials selections are not finalized, and as a result the system wet mass is still an estimate.

Table 2: MVP System Performance

Item	MVP Performance
Propulsion system volume	1000 cc
System lifetime	Not propellant limited
Spacecraft temperature range	Not propellant limited
Propellant	POM, gaseous MW = 30
Propellant Mass	660 g
Total propulsion wet mass	1000 g (est)
Nominal mass flow rate	8.2 g
Total thrust time	22 hr
Specific Impulse	83 s
Primary Thrust	6.7 mN
Total impulse	540 N-s
Spacecraft ΔV, M(initial) = 4 kg	150 m/s
Spacecraft propulsion power	35 W

CONCLUDING REMARKS

CUA has made major strides forward in developing the MVP electrothermal thruster which consumes an inert polymer propellant fiber. This technology retains performance characteristics competitive with other warm gas systems, but enables more accessibility to micropropulsion via dramatically reduced cost and the elimination of range safety concerns (no pressure vessel and an inert propellant). The MVP system draws from extrusion 3D printer technology and CUA's micro-resistojet CHIPS technology. Despite undergoing depolymerization and two separate phase changes, the system power requirements are manageable, demonstrating typical specific thrusts of 0.16 mN/W, and a specific impulse in excess of 100 s. Our design for a 1U system is predicted to have performance exceeding 500 N-s total impulse. The goal is to develop a self-contained flight-like prototype system over the course of the next year.

Acknowledgements

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