Monofilament Vaporization Propulsion (MVP)

SmallSat 2018

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CUA, L.L.C.
CUA (Champaign Urbana Aerospace) Synopsis

- CUA is a high tech engineering company engaged in bringing innovative advanced technologies to the market
  - Founded in 1998
  - Growth rate ≈ 15% per year
- Location: Champaign, Illinois
  - 10,000 sq. ft. mixed-use office/laboratory building
- Specialties
  - Space systems
  - Plasma and laser systems
  - Aerospace materials
  - Modeling and simulation
High TRL Warm Gas Thrusters

Propulsion Unit for CubeSats (PUC)
- Micro-plasma discharge thruster technology
- Flight qualified to TRL 6
- 8 units delivered to Air Force Research Lab in 2014

CubeSat High Impulse Propulsion System (CHIPS)
- Micro-resistojet technology
- Non-toxic “green” propellant (R236fa or R134a)
- Main propulsion + attitude control system (ACS) thrusters
- Dedicated propellant heater enables operation at < 0 °C ambient
- Feed dryer ensures 100% vapor delivery to plenum
- Pressure-controlled vapor plenum supplies all thrusters
- VACCO high-reliability, frictionless valves
  - Valve design tested to millions of cold gas firings
- Dual-fault tolerant against leakage
**Monofilament Vaporization Propulsion (MVP) System**

**Motivation:**
- Eliminate pressure vessel and valving
- **Lower cost**
- **No range safety concerns**
- Lower risk to CubeSat

**Overview:**
- Draws from extrusion 3D printing tech.
- Solid polymer propellant stored on “spool”
- Fed mechanically at desired rate
- Melted at a regulated temperature
- Evaporated and heated with resistojet from CHIPS (superheater)
Breadboard Operation

Solid → Liquid → Vapor

Heat Sink: PTFE lined barrel
Hot end: Controlled to 200 °C

20-50 °C → 200 °C → 900 °C

CHIPs style superheater
Nozzle

Heater Block
Barrel
Resistojet
Nozzle

Feed Motor
Propellant

Acetal (Polyoxymethylene, POM, Delrin)

- Decomposition to monomer (Formaldehyde)
- Formaldehyde (CH$_2$O) molecular weight – 30 g/mol
- 1.75 mm diameter
- Extrusion temperature 200° C
- Theoretical Isp @ 900° C, 80% nozzle efficiency – 132s
  - Decomposition issues this hot
- ~3.5 J/mg required to reach exhaust temp from solid propellant

From DuPont Delrin design guide

<table>
<thead>
<tr>
<th>Dose, Mrad</th>
<th>Tensile Strength, MPa</th>
<th>Tensile Strength, psi</th>
<th>Elongation, %</th>
<th>Izod Impact, J/m</th>
<th>Strength, ft-lb/in</th>
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<tr>
<td>0</td>
<td>69</td>
<td>10,000</td>
<td>15</td>
<td>75</td>
<td>1.4</td>
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<tr>
<td>0.6</td>
<td>67</td>
<td>9,080</td>
<td>11.5</td>
<td>53</td>
<td>1.0</td>
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<td>2.3</td>
<td>43</td>
<td>6,200</td>
<td>0.9</td>
<td>11</td>
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</table>
Feed System

- Geared BLDC motor
  - COTS drive electronics (for now)
  - Torque matched to 3D printer feed system used for thruster testing

- Spooled propellant
  - Similar to open-face fishing reel
  - Fixed spool minimizes torques on spacecraft
Nozzle Simulations

- BLAZE Multiphysics™ used to simulate MVP nozzle flows

- Calculations indicated large boundary layer (BL) in original 20-degree half angle nozzle due to low Reynolds # associated with MVP flow conditions

- Larger half-angles predicted to improve Isp by reducing fraction of nozzle filled by BL
  - Consistent w/ findings of Williams & Osborn [IEPC-2017-120]
Plume Simulations

- DSMC simulations by University of Michigan (Boyd)
- Nozzle exit profile in number density and velocity
Performance

- Around 50 thrust-stand-tested operating conditions during Phase I and II
  - Lower than 15W total system power demonstrated
  - > 100s specific impulse demonstrated
  - > 6.5 mN thrust demonstrated

- Extensive life testing performed
  - Narrower operation regimes ensure system life
  - Gradual, yet consistent clogging occurs from decomposition of formaldehyde
  - Redesigned nozzle, superheater, higher flow rate operation required to survive full propellant load

- Conditions listed at right tested to 140% life with 15 minute burns
  - Refine firing schedule to further increase life
  - Shorter burns can allow for higher specific impulse

### System Information

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Propulsion system volume</td>
<td>1U</td>
</tr>
<tr>
<td>System lifetime</td>
<td>Not propellant limited</td>
</tr>
<tr>
<td>Spacecraft temperature range</td>
<td>Not propellant limited</td>
</tr>
<tr>
<td>Propellant</td>
<td>POM, gaseous MW = 30</td>
</tr>
<tr>
<td>Propellant Mass</td>
<td>660 g</td>
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<tr>
<td>Total propulsion wet mass</td>
<td>1.2 kg (est)</td>
</tr>
<tr>
<td>Nominal mass flow rate</td>
<td>8.2 mg/s</td>
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<tr>
<td>Total thrust time</td>
<td>22 hr</td>
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<tr>
<td>Specific Impulse</td>
<td>83 s</td>
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<tr>
<td>Primary Thrust</td>
<td>6.7 mN</td>
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<tr>
<td>Total impulse</td>
<td>540 N-s</td>
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<td>Spacecraft ΔV, M(initial) = 4 kg</td>
<td>150 m/s</td>
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<tr>
<td>Spacecraft propulsion power</td>
<td>35 W</td>
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Summary and Status

- MVP has demonstrated reliable, consistent operation in bench-testing
  - 6.7 mN, 540 N-s in 1U system
- Inert propellant with solid, spooled storage → no pressure vessel, no valving
  - **Dramatically lower risk**
  - **Significantly lower system cost**
- Flight-like hardware and electronics in manufacturing
- Critical systems life tested at system performance levels competitive with warm-gas systems
Acknowledgements

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- Iain Boyd (University of Michigan)