A Discrete, Multiphase Flow Approach to Monopropellant-Based Micropropulsion

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WHAT ARE MICROTHRUSTERS?

- Nanosatellites (<10 kg) have been proposed for a variety of future missions that may require formation flying and precise positioning

- Station keeping maneuvers are performed through discrete impulse bits

- Traditional propulsion systems are unable to meet the requirements of these missions

Microthrusters
MONOPROPELLANT MICROPROPULSION CHARACTERISTICS

### Propulsion System Requirements

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<table>
<thead>
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<tbody>
<tr>
<td>Power Consumption</td>
<td>1 - 5 W</td>
</tr>
<tr>
<td>Size</td>
<td>1 - 10 cm³</td>
</tr>
<tr>
<td>Mass</td>
<td>for nanosat &lt; 10 kg</td>
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<tr>
<td>Thrust</td>
<td>1 - 500 μN</td>
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<tr>
<td>Impulse bit</td>
<td>1 - 1000 μN · s</td>
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- Major obstacle to implementation is micro-scale valves

- “...the realization of reliable, high-force and leak-tight valves in MEMS poses even greater challenges than the thruster itself”[1]


A ‘DISCRETE’ MONOPROPELLANT CONCEPT

McCabe et al., 2011

Cross et al., 2011

Hitt et al., 20001
Injecting an inert gas (air) creates a downstream pinch-off.
This process is periodic and controllable.
During a typical micro-valve cycle, many slugs are formed.
STEADY STATE OPERATION EXPERIMENTAL SETUP

- Using this setup, inlet parameters are varied
- Slug formation is captured using high speed imaging (~15k-20k FPS)
- Slugs are analyzed for size and frequency
EXPERIMENTAL RESULTS

By controlling the flow rates of the gas and fuel, thrust can be specified at levels much lower than is possible with traditional micro-valves.

High Thrust Operation

Low Thrust Operation
3D SIMULATION RESULTS

Outlet

Fuel Inlet

Fuel Inlet

Air Inlet

\[ t = 0.2 \, ms \]
3D SIMULATION RESULTS

$t = .6 \text{ ms}$

Gas Bubble

Fuel Slug
ANIMATION OF SLUG FORMATION
Inlet Conditions:
- Air Inlet Velocity
  - Ranges between .02-.04 m/s

Properties:
- Surface Tension (2D)
  - Varies with temperature
  - Ranges between .05-.10 N/m
- Contact Angle (2D)
  - Varies with wall roughness
  - Ranges between 140° and 180°
- Fuel Viscosity (2D)
  - Varies with temperature
  - Ranges between 0.6 and 1.8 cP
- Depth Effects (3D)
  - Manufacturing Consideration
  - Ranges between 10 and 50 microns

105 2D Cases & 10 3D Cases
EFFECT OF REPEATED CYCLES

First Valve Opening

Second Valve Opening

Slug length remained constant over repeated valve cycles
A DISCRETE, MULTIPHASE FLOW APPROACH TO MONOPROPELLANT-BASED MICROPROPULSION

SAMPLE OF TRANSIENT SIMULATION RESULTS
Inlet Conditions:
- Air Inlet Velocity
  - Ranges between .02-.04 m/s

Properties:
- Surface Tension (2D)
  - Varies with temperature
  - Ranges between .05-.10 N/m
- Valve Opening Profile (2D)
  - Design Consideration
  - Ranged between 20%-100%

55 2D Cases
PROPOSED DESIGN: MONOPROPELLANT THRUSTER

Catalytic chamber

- Monopropellant
- Monopropellant slug
- Inert fluid
- Catalyst
- Supersonic nozzle

A DISCRETE, MULTIPHASE FLOW APPROACH TO MONOPROPELLANT-BASED MICROPROPULSION
SEM IMAGES OF PILLARS IN CATALYTIC CHAMBER
THERMAL IMAGING OF MICROCHANNEL

- Using thermal imaging the temperature profile can be determined.

- Temperatures as high as 850°C have been recorded in the lab.
IMAGE OF POST-CHAMBER DECOMPOSITION

Flow Direction

Bubbles are Water Vapor and Oxygen
SUMMARY & FUTURE WORK

• Experiments and simulations have demonstrated conceptual feasibility of multiphase fuel delivery for effective throttling of fuel mass flow rate
  - Reduced mass flow rate by up to 50% compared to traditional throttling
  - Fuel flow rates predict a thrust of 75 μN
  - Operation is stable over many valve cycles

• Successful proof-of-concept of the nano-rod application and improved decomposition
  - Thermal images show temperatures approaching the adiabatic flame temperature of hydrogen peroxide
  - High speed video shows transition from liquid fuel to high temperature gasses

• Future work includes experimental and numerical studies of the integrated sub-systems
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Questions?