Design and Development of a Multi-Mode Monopropellant Electrospray Micropropulsion System

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Introduction

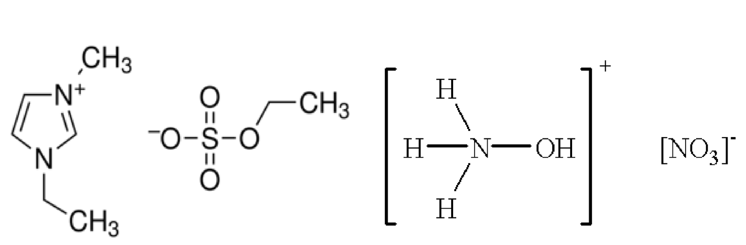
Most spacecraft propulsion concepts can be classified into two categories: chemical and electric. Chemical propulsion relies on chemical reactions and can produce high thrust, but requires a large amount of fuel. Electric propulsion uses electromagnetic fields to accelerate ionized gases and is very fuel efficient, but produces small amounts of thrust and thus long trip times. Our research is focused on developing propulsion systems with both chemical and electric modes available. For micropropulsion applications, minimum propulsion system mass is of utmost importance. Optimum multi-mode propulsion systems will make use of shared propellant and hardware used for both propulsive modes.

Motivation

- Chemical AND electric propulsion available in a single package
- Can provide attractive enhanced mission flexibility for smallsats
- Allows for significant mission changes on-orbit
- Enables missions not achievable by chemical or electric propulsion alone
- Many different types of manuevers available with a single propulsion system

Propellant

- We have developed propellants that are capable of both chemical monopropellant and electric electrospray propulsion
- One is a mixture of ionic liquid 1-ethyl-3-methylimidazolium ethyl sulfate ([Emim][EtSO$_4$]) fuel mixed with hydroxylammonium nitrate (HAN) oxidizer. This is a non-toxic 'green' monopropellant with properties similar to AF-M315E and LMP-103S
- Rapid thermal and catalytic decomposition has been demonstrated in our laboratory batch reactor. Additionally, we have experimentally determined the reaction rate on various catalyst material and the linear burn rate



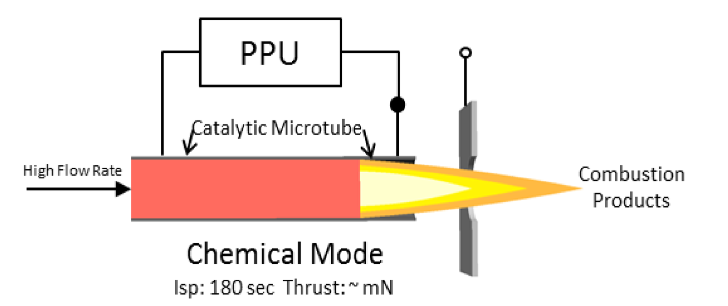
[Emim][EtSO4] HAN

Propellant as Synthesized

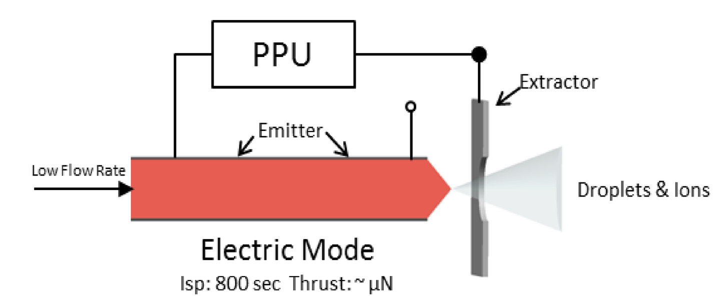
Propulsion System Design

Multi-Mode Smallsat Propulsion

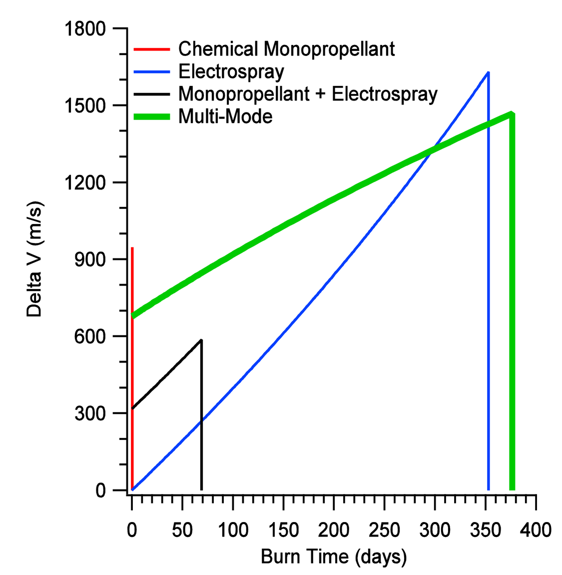
- A single propulsion thruster operable in catalytic chemical or electrospray electric modes
- Both modes use same non-toxic, green ionic liquid propellant (properties similar to AF-M315E)
- Slightly lower performance than state-of-the-art in each mode separately, but similar mass/volume/power requirements



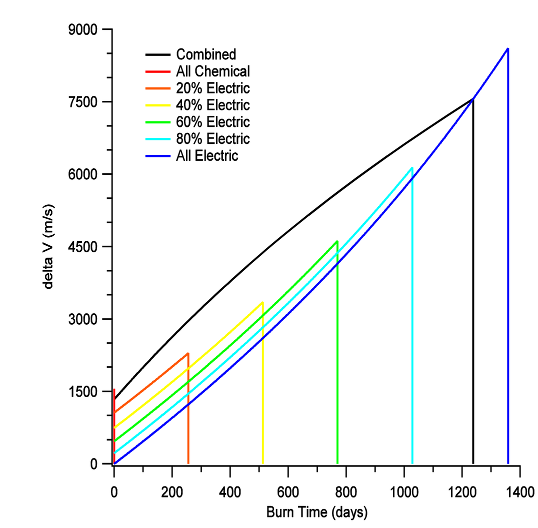
Chemical Mode
Isp: 180 sec Thrust: ~mN



Electric Mode
Isp: 800 sec Thrust: ~μN



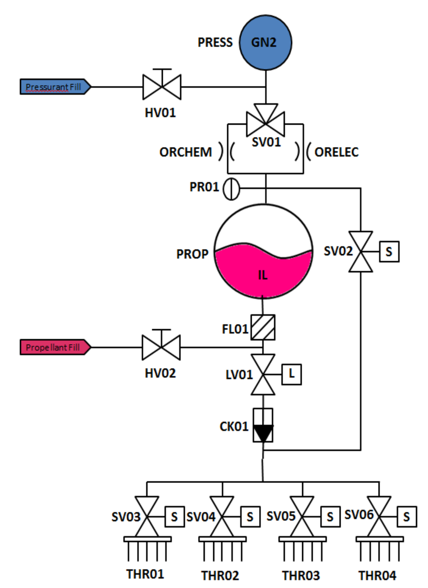
Design space for 6U CubeSat with 3 kg payload



Design space for 180 kg satellite with 65 kg payload

Flexible Mission and System Design

- Huge mission design space available with a single propulsion system
- Bridges the gap between chemical and electric propulsion
- Shared propellant between chemical and electric modes significantly enhances mission design space
- Allows for varied selection of maneuvers as mission needs arise *on-orbit*
- Thruster size can be adjusted by simply adding or subtracting emitters. Significant flexibility in thrust while keeping same spacecraft interface
- Scales from pico- to micro-satellites. Beneficial for both attitude control and orbit raising manuevers



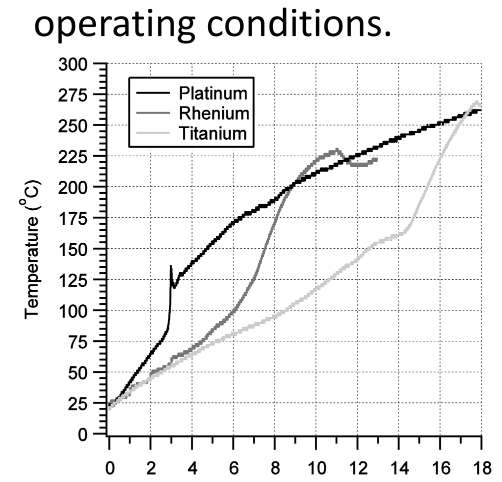
System	Dry Mass (g)	Volume (U)	Power (W)	Thrust (mN)		Specific Impulse (s)	
Monopropellant	1200	0.5	15	500		225	
Electrospray	1150	0.5	15	0.7		800	
Monopropellant + Electrospray	2350	1	15	500	0.7	225	800
Multi-Mode Integrated	1400	0.5	12	1000	0.6	180	780

Feed System Design: The baseline system consists of four thruster pods for attitude control. Isolation valves meet military standards based on propellant hazard level. Additional valves are included to facilitate flow modulation and mode selection.

Thruster Development and Testing

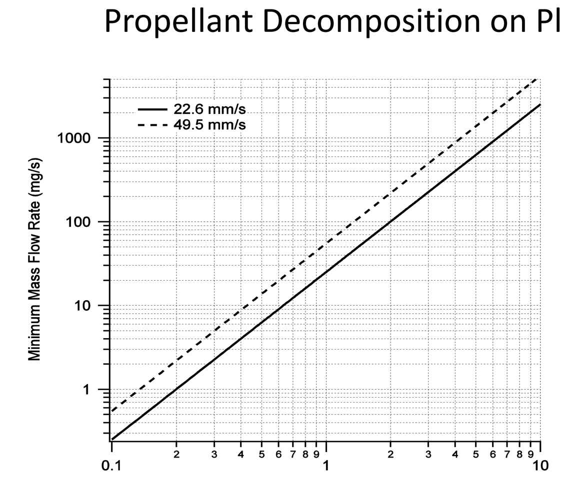
Chemical Mode

- Experimentally determined propellant reaction rate and linear burn rate.
- Designed microtube thruster experiment. Currently built and in testing.
- Will experimentally determine ignition criteria and steady state operating conditions.



Material	E/k_B (K)	A (1/sec)
Platinum	10771 ± 503	(2.14 ± 0.23) x 10^{10}
Rhenium	16170 ± 107	(2.23 ± 0.26) x 10^{10}
Titanium	30111 ± 797	(2.64 ± 0.26) x 10^{10}

Propellant Decomposition on Platinum, Rhenium, and Titanium Surfaces

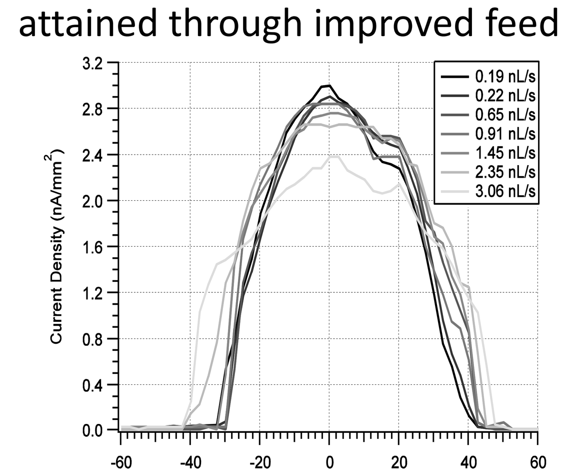


Minimum Feed Rate to Prevent Flashback

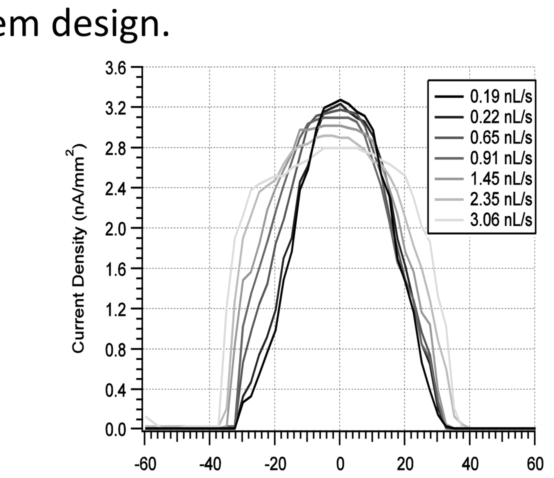
Microtube Thruster in APLab Vacuum Chamber

Electric Mode

- Successfully demonstrated electrospray of the [Emim][EtSO$_4$]/HAN propellant in a capillary type emitter, extracting both cations and anions.
- Attained 412 seconds Isp at the lowest flow rate attainable with this propellant in the experimental setup at AFRL Kirtland.
- Lower flow rates, and specific impulse in excess of 1000 seconds can be attained through improved feed system design.



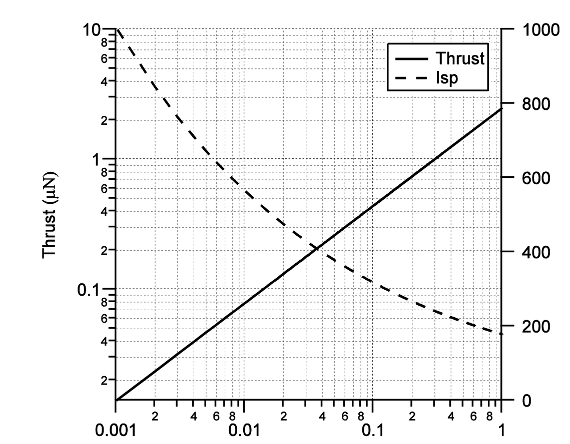
Angle Resolved Cation Emission



Angle Resolved Anion Emission

Mass Flow (ng/s)	Average Thrust (μN)	Power (mW)	Isp (sec)
269	1.09	2.22	412
312	1.20	2.31	390
922	2.32	2.96	255
1291	3.18	3.96	250
2057	4.49	4.96	222

Experiment Thrust and Isp



Extrapolated Thrust and Isp

Future Work

- Currently at TRL 2. Microtube demonstration will bring technology to TRL 3
- Designing a combined microtube-electrospray thruster to demonstrate back-to-back operation of each thrust mode
- Developing thruster as primary payload for Missouri S&T Satellite Team (MSAT) in AFRL Nanosat 9 competition and NASA USIP mission
- Performing tests to quantify hazard level and qualify propellant for spaceflight per industry standards.

Summary

Ionic liquid mixtures capable of both chemical monopropellant and electrospray propulsion have been selected, designed, and synthesized. Rapid decomposition of these propellants has been demonstrated in a laboratory batch reactor and reaction and burn rates have been quantified. A multi-mode propulsion system has been designed based on performance of these propellants in both chemical and electric modes. The propulsion system uses the same propellant for both chemical and electric propulsion modes and utilizes shared tanks, lines, valves, and thruster hardware. This results in system-level performance far exceeding that of separate, state-of-the-art thrusters despite mode-specific performance deficits. Furthermore, this system can meet mission requirements for a wide range of potential small satellite missions. Thruster testing of both chemical microtube and electric electrospray modes is ongoing with TRL 3 expected to be achieved by Fall 2016. Data from these experiments will be used to design the nominal thruster and flight-like propulsion system configuration.

Supported by: