John
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FILM-EVAPORATION MICROTHRUSTER FOR CUBESATS

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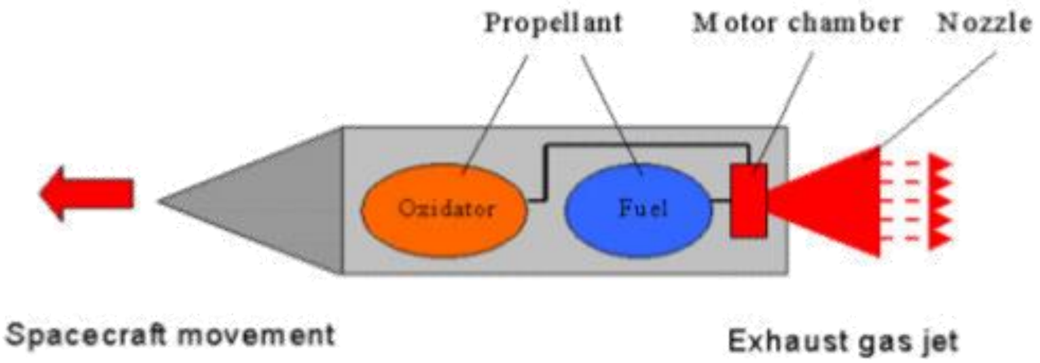
Contents

John Sebastian

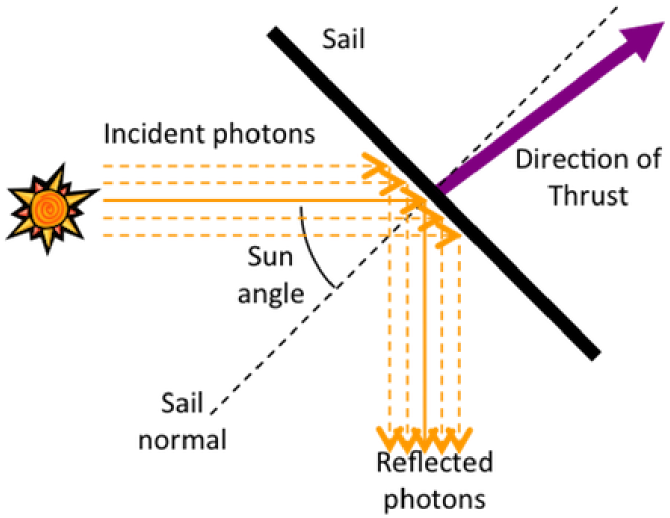
Introduction

John Sebastian

- Thrusters:
  Propulsion device for launch, orbit control and attitude control
- Reaction- Control System:
  - Reaction Jets
  - Solar Sails
  - Magnetorquers (magnetic coils)
  - Momentum-Transfer Devices (reaction-, flywheels)



Reaction Jet



Solar Sail

Introduction

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Magnetorquer

Reaction Wheel

Thruster Principle

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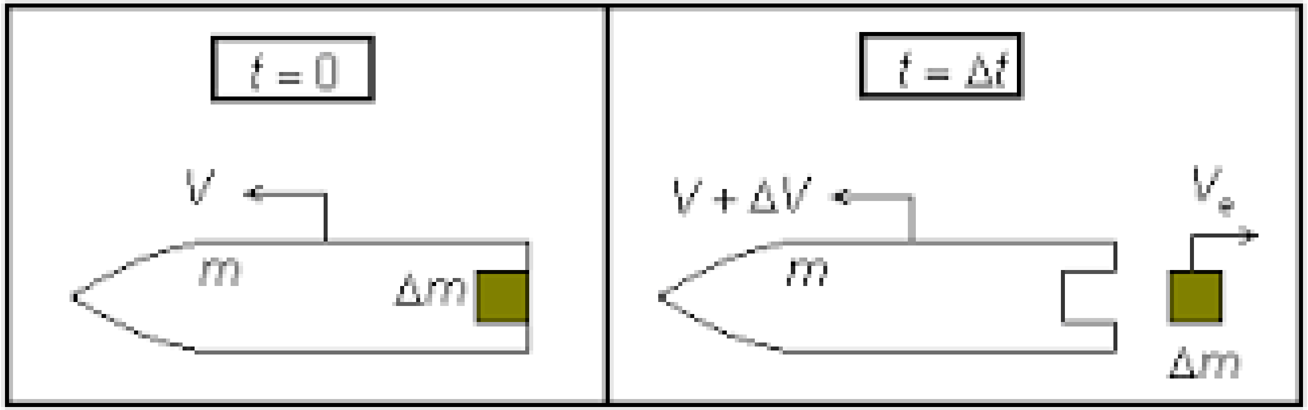
- Action- reaction force pair generation by expulsion of mass from the system
- Conservation of momentum

$$m \cdot \Delta v = -v_e \cdot \Delta m$$

- Basic rocket equation- the Tsiolkovsky equation

$$\frac{m_f}{m_{sc}} = e^{\frac{-\Delta v}{v_e}}$$



Parameters

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Thruster Performance Factors:

- The most useful parameter for determining thrust engine (or thruster) performance is **Specific Impulse**:

$$I_{sp} = \frac{F}{g * \dot{m}} \quad [s]$$

- **Effective Exhaust Velocity**

$$v_e = \frac{F}{\dot{m}} \quad [m/s]$$

- **System-specific Impulse, I_{ssp}**

$$I_{ssp} = \frac{I_{tot}}{m_{PS}} \quad [N.s/kg]$$

- **Delta V**

$$\Delta v = \int_{t_0}^{t_1} \frac{|T(t)|}{m(t)} \, dt \quad [m/s]$$

Satellites

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- Different ways to classify artificial satellites – by function, type of orbit, cost, size, etc.
- Classification by mass is useful because it has a direct bearing on the launcher vs. cost trade- off.

Category	mass range (kg)
large satellite	> 1,000
medium-sized satellite	500-1,000
minisatellite	100-500
microsatellite	10-100
nanosatellite	1-10
picosatellite	0.1-1
femtosatellite	< 0.1

CubeSats

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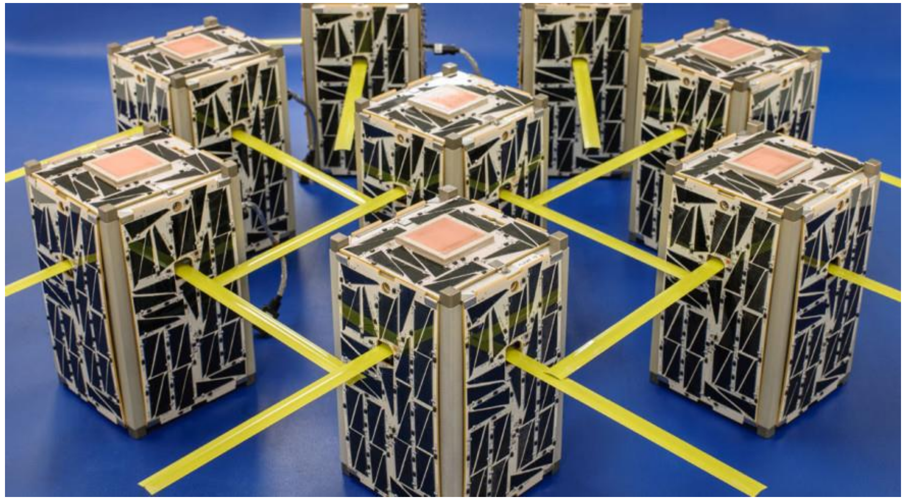
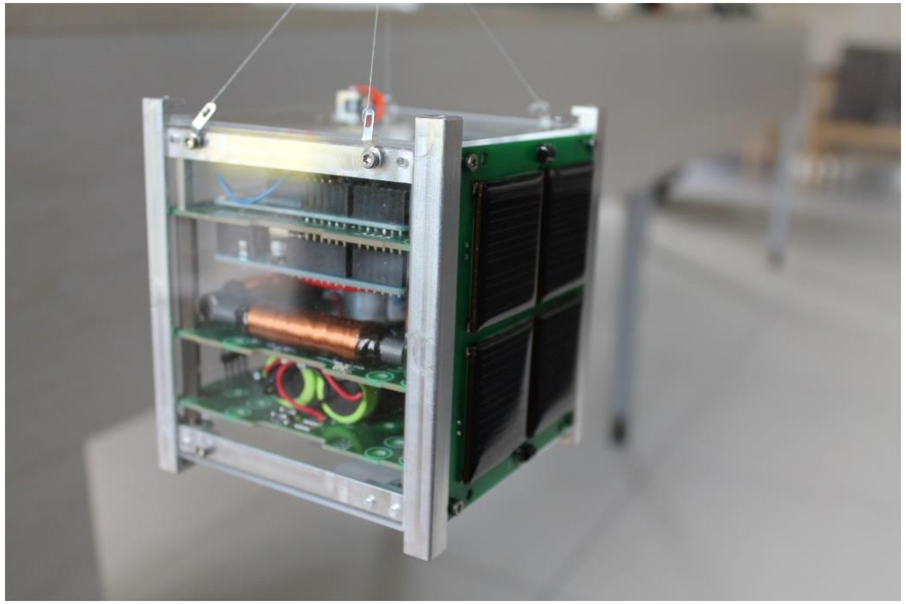
- A CubeSat (U-class spacecraft) is a type of miniaturized satellite for space research that is made up of multiples of 10×10×11.35 cm cubic units and mass no more than 1.33 kilograms per unit

- **Reaction wheels** are commonly utilized for their ability to impart relatively large moments for any given energy input, but reaction wheel's utility is **limited due to saturation**, the point at which a wheel cannot spin faster

- Magnetorquers which run electricity through a solenoid to take advantage of **Earth's magnetic field to produce a turning moment**





Design Objectives- Micro Thrusters

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Designing a micro thruster involves improving or decreasing the following factors

- Specific Impulse
- Delta V
- Mass and Volume
- Minimum accessories
- Longevity
- Self locking reservoir
- Smooth Thrust curve
- Simple Control System
- Low Reaction Time

Thruster Types

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- **Chemical Propulsion Systems** are designed to satisfy high thrust impulsive maneuvers. They are associated with lower specific impulse compared to their electric counterparts, but have significantly higher thrust to power ratios.
    - Hydrazine
    - Warm and Cold gas
    - Non toxic gas
    - Solid Motor
- **Electric Propulsion Systems**
- Depending on thruster technology, specific impulse for electric propulsion can range between 700-3000s. Thrust is low meaning long manoeuvre times.
- More suitable for small correction manoeuvres and attitude control applications due to low impulse bits
    - Resistojets
    - Electrosprays
    - Ion Engines
    - Pulsed Plasma and Vacuum Arc Thrusters
    - Hall Effect Thrusters

FEMTA

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FEMTA: Film Evaporative MEMS Tunable Array

- exploits the small scale surface tension effect in conjunction with temperature dependent vapour pressure
- a thermal valving system for effective propulsion in the sub- milli- Newton range
- The local vapour pressure is increased by resistive film heating until it exceeds meniscus surface tension strength in the nozzle inducing vacuum boiling
- stagnation pressure equal to vapour pressure is reached at that point which is used for propulsion
- The heat of vaporization is drawn from the bulk fluid and is replaced by either an integrated heater or waste heat from the vehicle providing a thermal control capability

FEMTA- Principle

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- FEMTA operation relies on exploitation of microscale effects of surface tension and its balance with stresses created by the vapor pressure
- A critical size of capillary for which the surface tension is being balanced by normal stresses due to the pressure drop across the boundary can be estimated from the Young-Laplace equation as
-

$$d = \frac{2\,\tau cos\theta}{p_{vap}}$$

d is the gap size of the annular or slit capillary
τ is the surface tension
p_{vap} is vapour pressure which depends exponentially on the temperature of the liquid film

- For water the critical gap size varies from d=60 μm to 10 μm for film temperatures from 20 to 50 °C.
- When the capillary size is above the critical value a rapid evaporation can be triggered.
- This provides low-power, compact and highly controllable thermal valve

FEMTA- Principle

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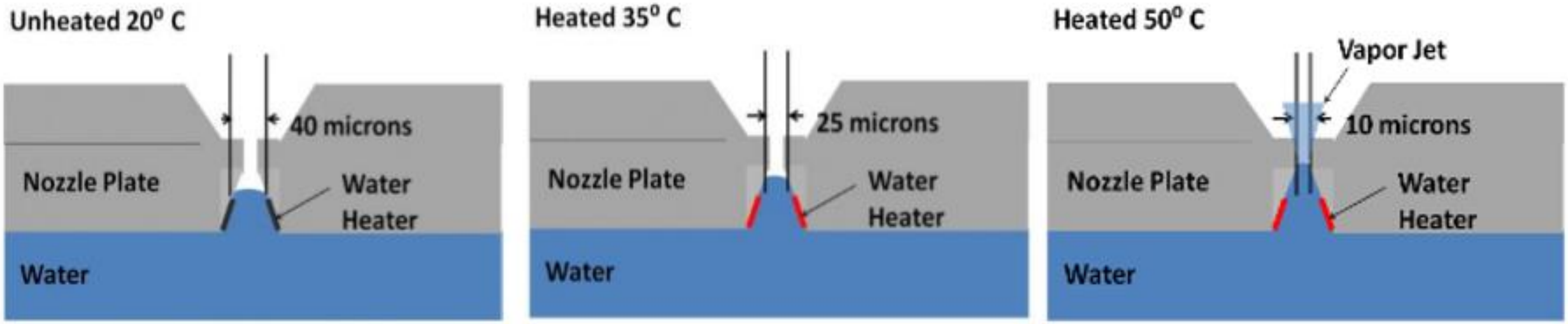

Schematic of 2D FEMTA operation
Meniscus position changes with the local heating of the capillary wall. A single array element is shown.

- FEMTA thermal valve exploits the same physics of surface tension control by heating fluid confined in a micro- capillary as the existing thermal inkjet (TIJ) technology
- Micro- heaters propel ink droplets by rapidly expanding gas bubbles formed by fast localized vaporization. The phase change energy is transferred from the device to the vapour.

FEMTA- Geometry

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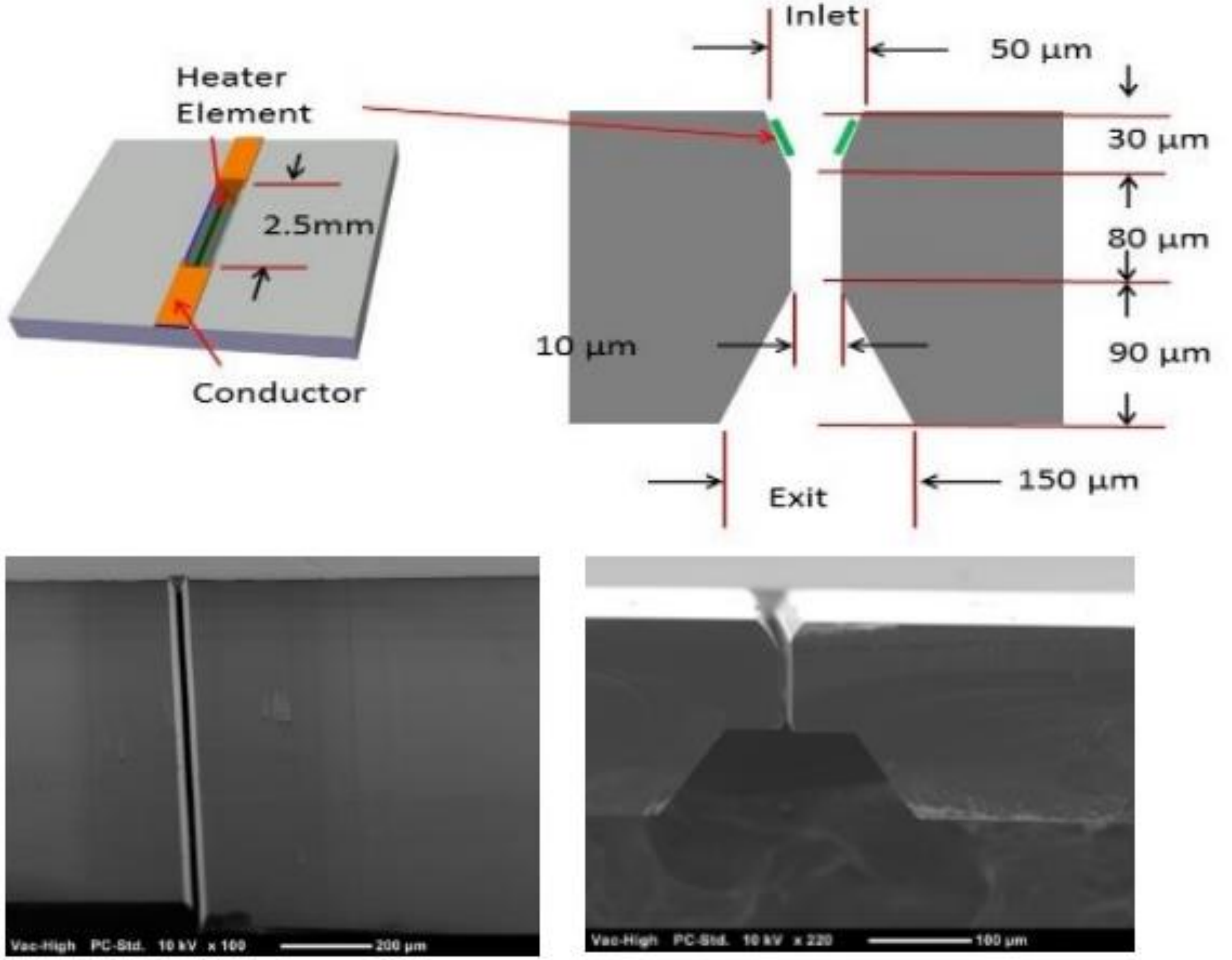

2 D nozzle with AR = 8 (top)
SEM images of top view (bottom left) and cross section (bottom right)

FEMTA- Geometry

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- **Gen 1**: aspect ratios of 2 (Type A) and 8 (Type B) for the throat, were chosen as the lower and upper limits that could be feasibly fabricated
- Fabrication required fewer lithography masks and thus fewer production steps
- The conductor and heating elements were insulated from the substrate by a 500 nm thick layer of silicon oxide
- The heaters were nichrome, 700 nm thick and 10 μm wide

- **Gen 2**: increase in the thickness of heater film by a factor of 2.
- This would allow twice the current flow and four times the power dissipation at the same voltage which would mean reduced current density and voltage need to be applied.
- Increase in insulation thickness by a factor of 4 to reduce heat loss from the substrate
- Intermediate AR of 4 and 6 introduced

FEMTA- Geometry

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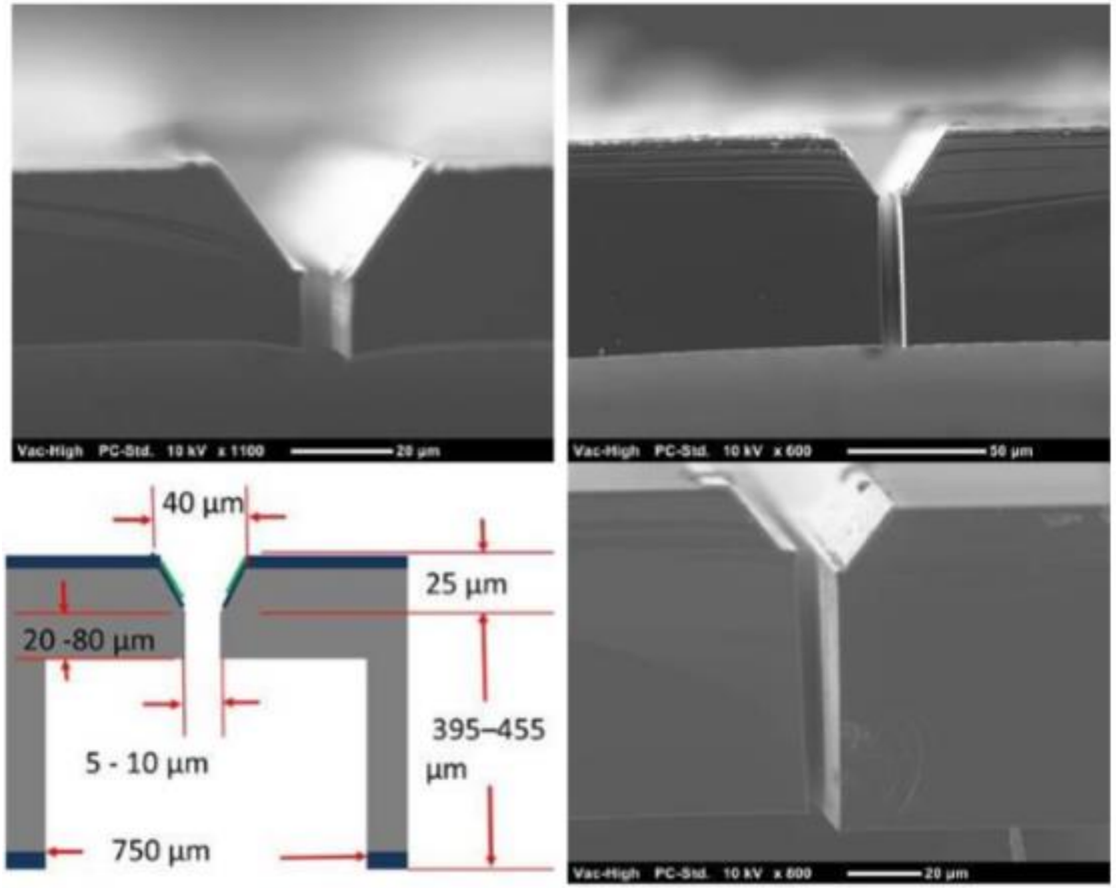
- **Gen 3**: nozzle fabricated on a 500 μm thick wafer for robustness

- Nichrome was replaced by vanadium as heater material due to
  - uneven etch rates of the nichrome alloy
  - High reactivity with nitric acid, acetic acid, phosphoric acid solutions, and commercial etchants, creating undercuts and open circuits.
  - Galvanic corrosion

- After the fabrication recipe was validated, Platinum, the choice material for MEMS replaced Vanadium



Clockwise from top left: AR-2, 6, 8; the schematic

FEMTA- Fabrication

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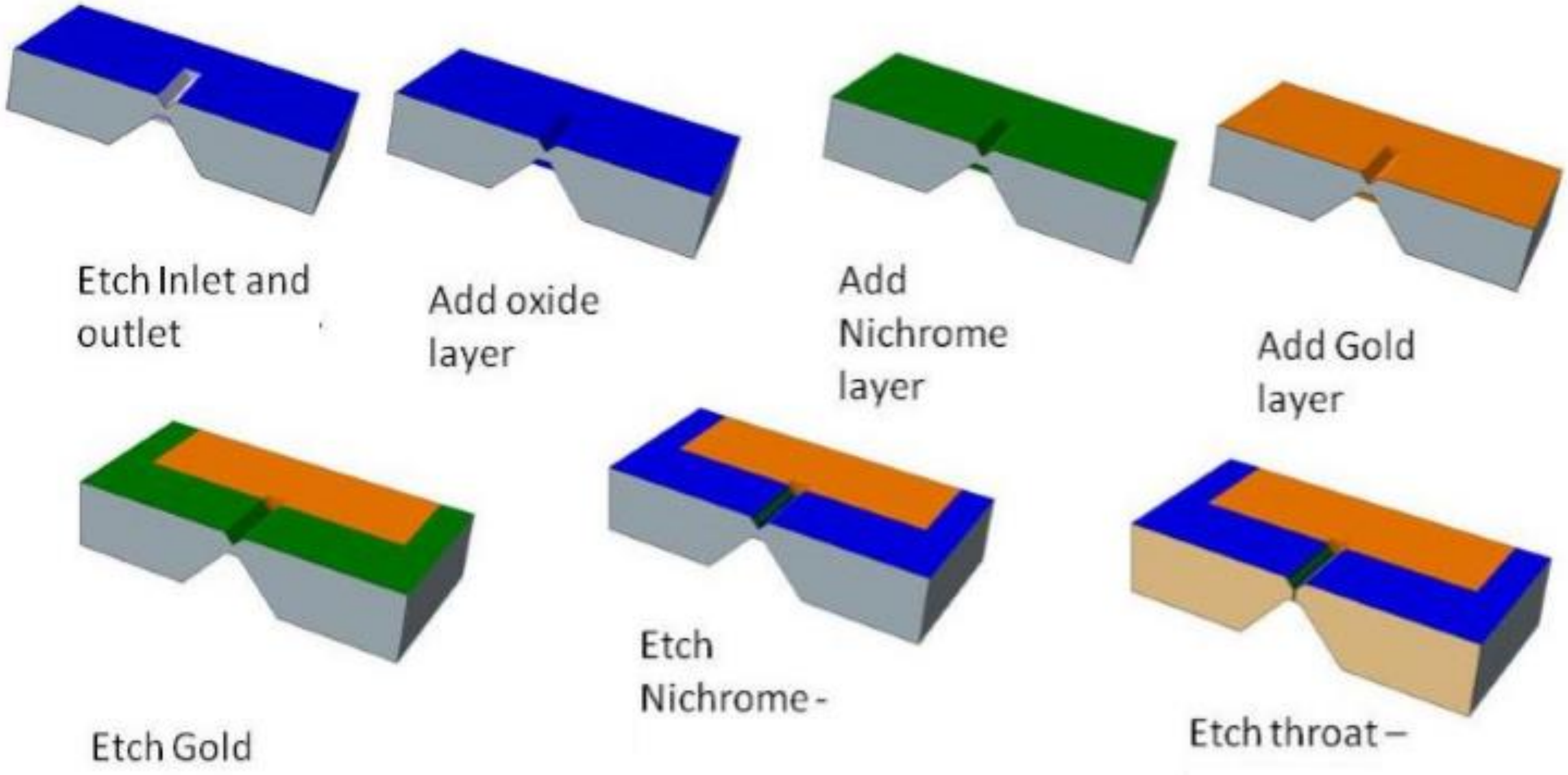

Deposition and Etch steps

FEMTA- Fabrication

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1. Nozzle Inlet/Exit Lithography
2. RIE Etch Nozzle Silicon Oxide Mask
3. Wet Etch Nozzle Inlet/Exit
4. Deposit Silicon Oxide
5. Deposit Heater/ Conductor Material
6. Conductor Lithography
7. Wet Etch Conductor
8. Heater Material Outside Lithography
9. Wet Etch Outside Heater Material
10. Heater Material Inside Lithography
11. Wet Etch Inside Heater Material
12. RIE Etch Oxide
13. Nozzle Throat Lithography
14. DRIE Etch Silicon Nozzle Throat
15. Wet Etch Oxide Nozzle Exit

FEMTA- Performance

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Thruster Type	I_{SP}	Thrust	Power	Voltage	Size*	Mass*
Cold Gas	40-80 s	0.5-50 mN	~ 1 W	<20 V	0.1-10cm^3	0.01-0.5kg
Electrothermal	50-250 s	≤200 mN	5-300 W	1-10 V	1-25 cm^3	0.1-1kg
Liquid/Solid	100-315 s	1μ-200 mN	--	--	0.1-10cm^3	0.01-0.5kg
Electromagnetic	200-3,000 s	0.03-2 mN	≤ 10 W	1-10 kV	0.5-100cm^3	0.06-0.5 kg
FEEP/Colloid	450-8,000 s	1μ-.1 mN	10-100 W	1-10 kV	~100 cm^3	0.1-1 kg
Hall/Ion	300-3,700 s	1-20 mN	50-300 W	0.1-1 kV	≤5 cmφ	≤ 1 kg
Electrospray array	~ 3,000 s	≤13 μN	175 mW	0.5-2kV	113 mm^2	5 g
FEMTA	**50 – 60 s**	**≤500 μN**	**70 mW**	**<5 V**	**0.05 cm^3**	**<.1 g**

Comparison with other micro thruster types

FEMTA- Performance

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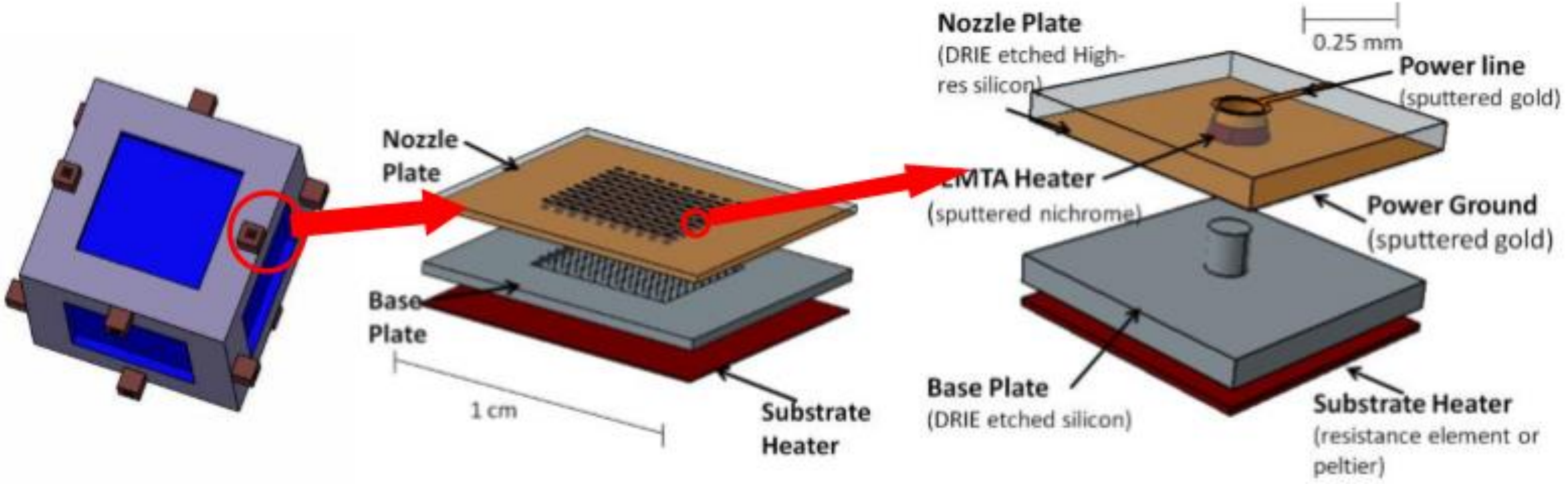
- A 1 Watt FEMTA unit contains a 10x10 array of thrusters
- a total system dry mass of <1 g and a volume <2 cm^3 which includes propellant tank and valving
- The design cooling power of a unit is 10 Watt, while the thrust is about 200 μN with a resolution of 3 μN and a specific impulse of 63 sec
- Twelve FEMTA units placed on a CubeSat provide 3-axis attitude control
- A single FEMTA unit with a 1 g propellant can also provide a delta-V of 0.6 m/s for 1 km altitude change for a 1 kg spacecraft in LEO



FEMTA- Testing

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FEMTA- Testing

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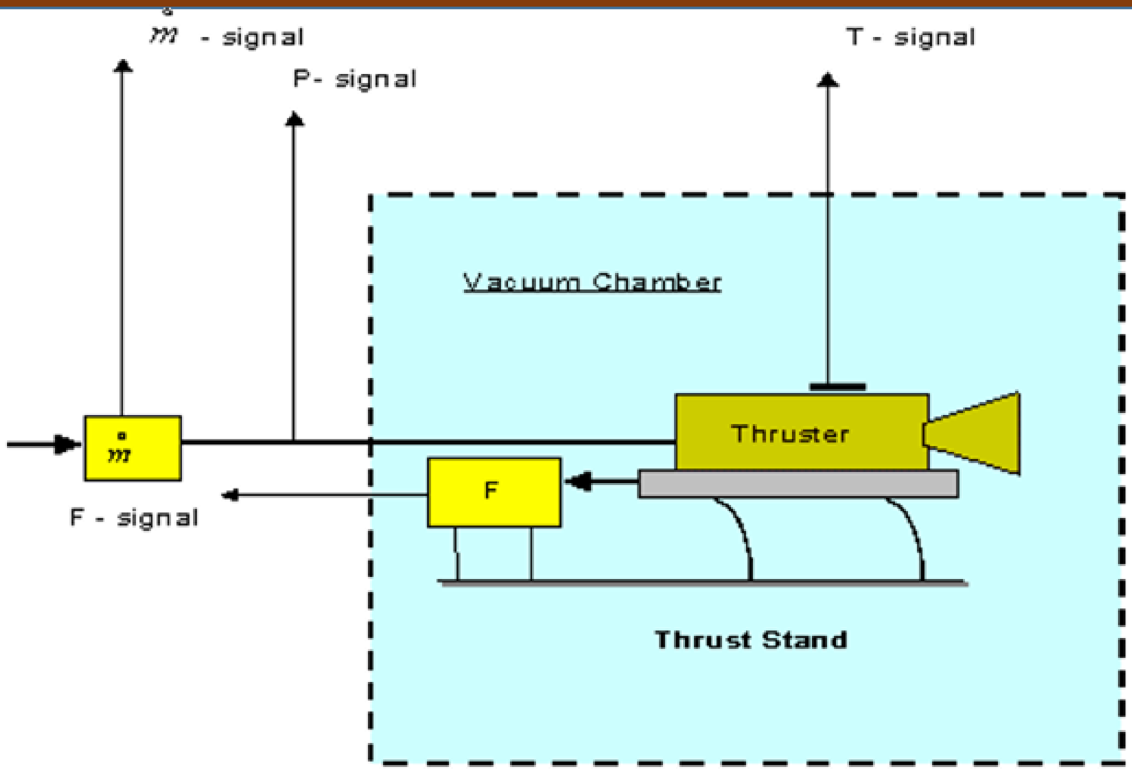

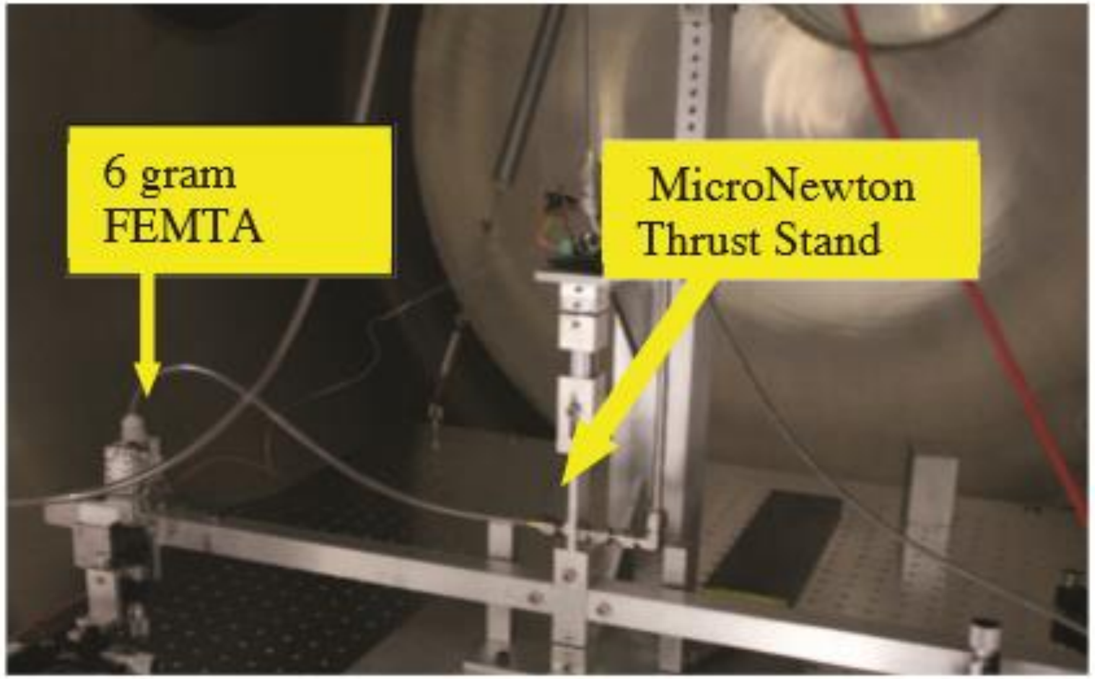

A test vessel was constructed from PTFE to provide propellant and power connections to the nozzles. The vessel was then attached to an arm of the micro- Newton thrust stand installed in a 4.2 cubic meter vacuum chamber.

The stand is a torsional balance type and uses an electrostatic fin assembly for calibration and an LVDT for displacement

FEMTA- Test Results

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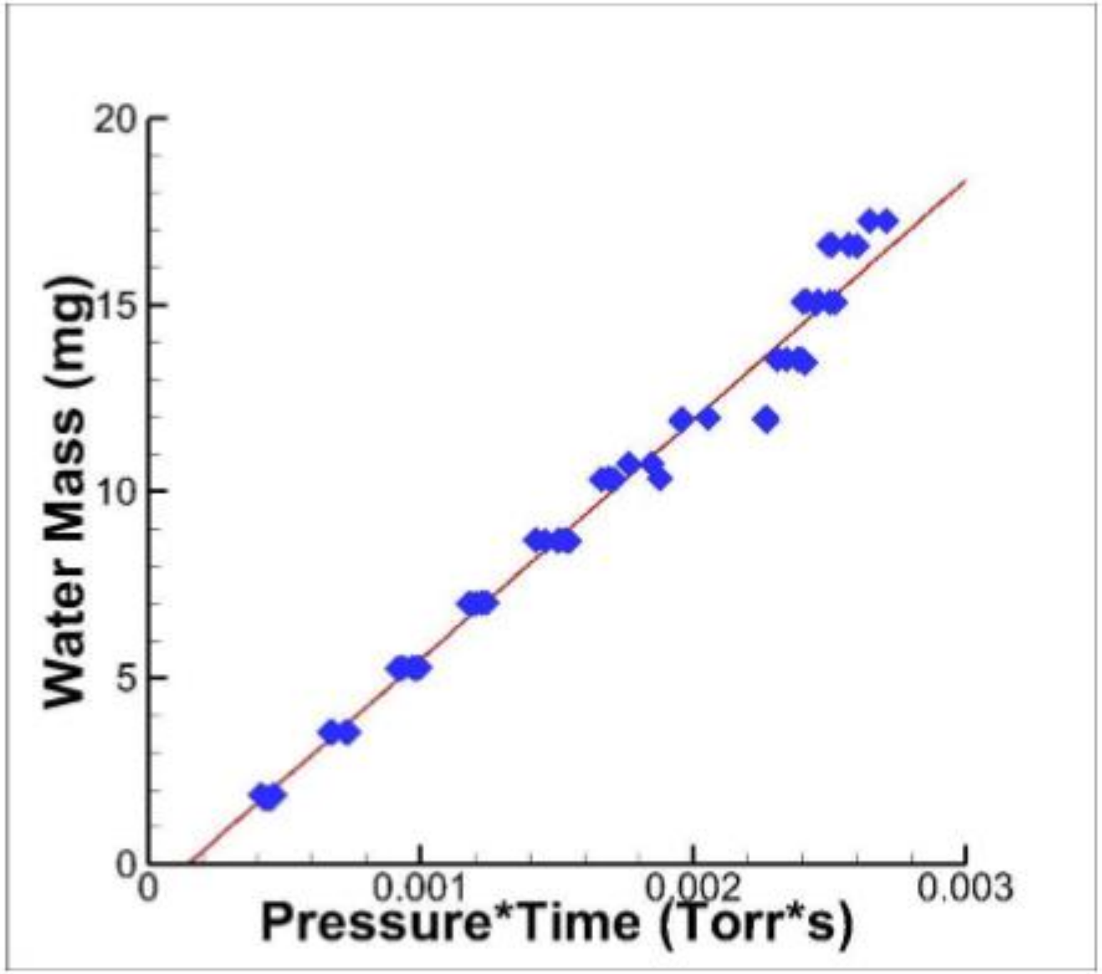
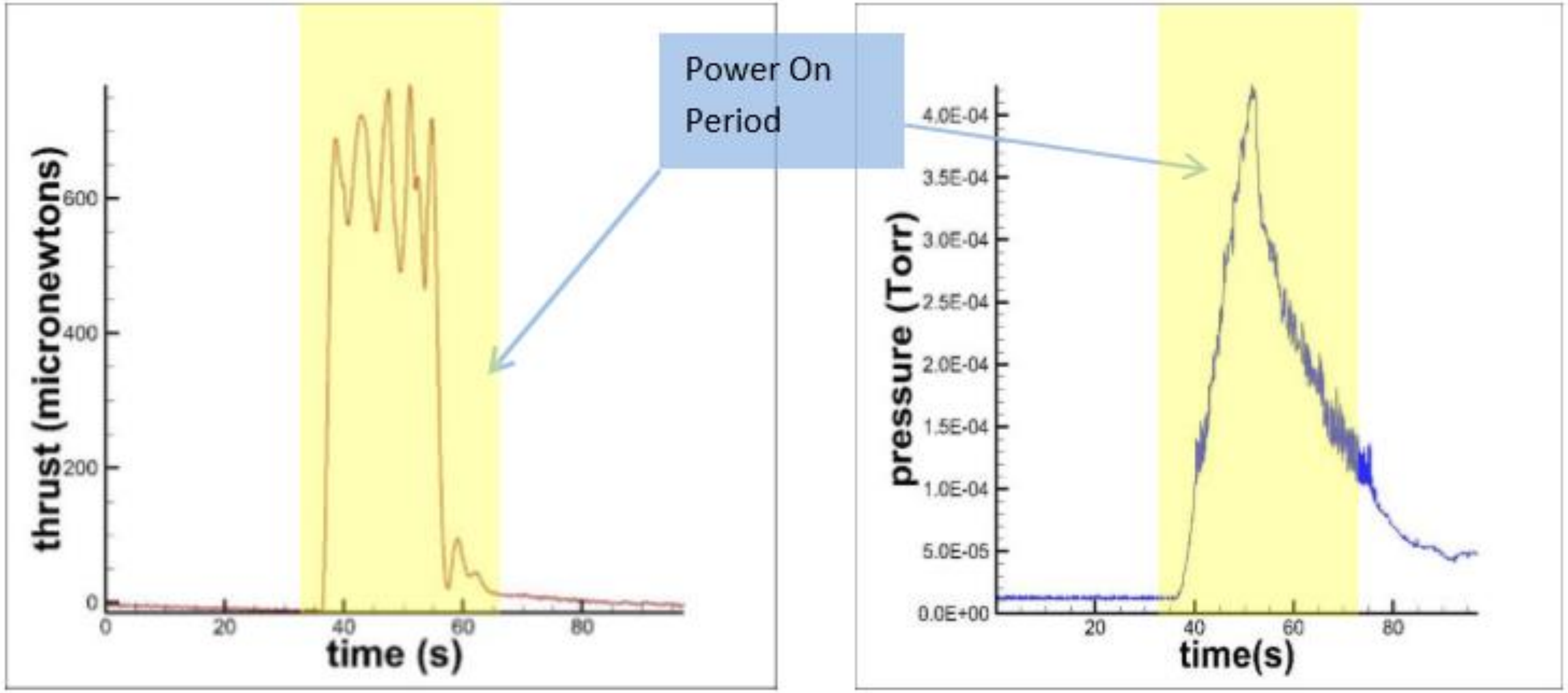
- Mass flow measurements for the thrust test were performed indirectly.
- The vacuum chamber was evacuated to base pressure of 5 microTorr and measured amounts of pure nitrogen were introduced over a specific period.
- The pressure change was integrated over the time required for rebound and a linear best fit was found.
- The ion gauge pressure was adjusted from nitrogen to water vapour using the gas correction factor of 1.12 and the mass was adjusted using the ratio of molecular weights.



FEMTA- Test Results

John Sebastian

- The vanadium heaters could only be energized a limited number of times before oxidation destroyed them.
- These runs however clearly showed the thermal switching effect in action. Power was applied for 31 seconds after a 34 second wait.
- Total impulse is 11.4 mN·s and total mass is 38 mg giving an I_{sp} of 30.6 seconds.



Thrust and Chamber pressure history showing switching

FEMTA- Test Results

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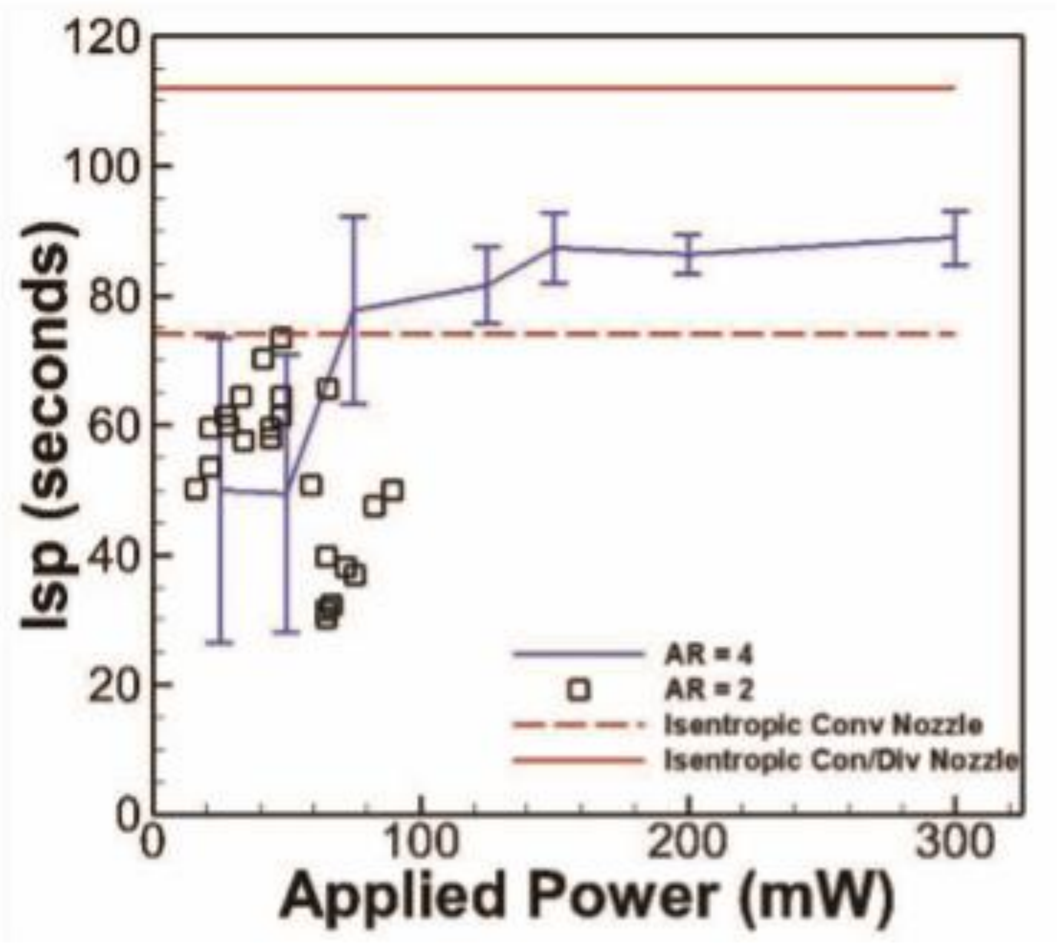
- Thrust values for third generation AR~2 models were inconsistent and had reaction times up to several seconds to power commands
- The thrust levels attained however were hundreds of microNewtons with only tens of milliwatts input
- AR ~ 4 devices were responsive within 200 milliseconds and provided much more consistent and steady thrust with a thrust/power ratio of 230 µN/W
- I_{sp} vs applied power indicates an asymptote for the AR ~ 4

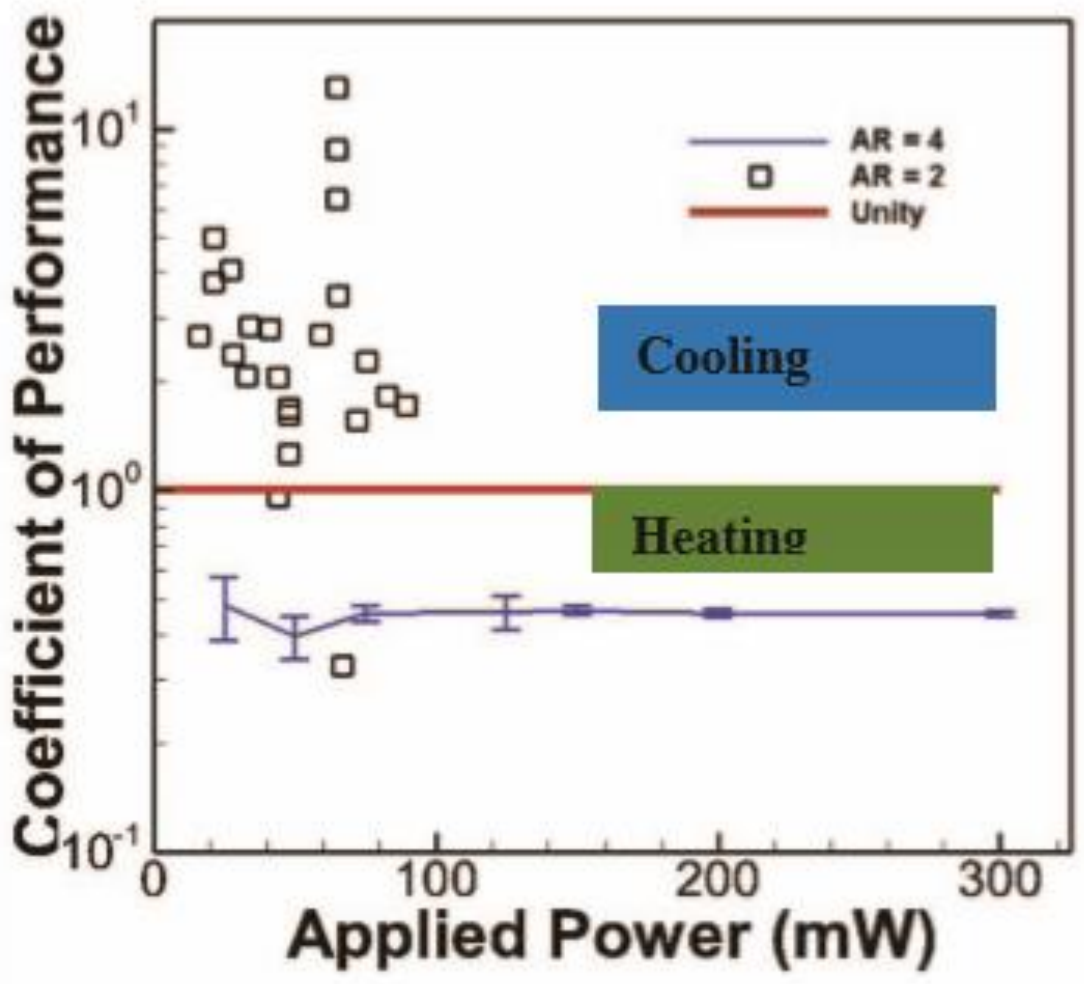


Impulse – Power graph for AR 2, 4 thrusters

FEMTA- Test Results

John Sebastian

- The coefficient of performance is the ratio of cooling power to power input
- The mass flows were much higher for the AR~2 units indicated by the low I_{sp} but at the same input power produces an enhanced cooling function which may be valuable for thermal control on small satellites
- The AR~4 had a net heat gain which may have been imparted to the vapour which explains the increased Isp



Coefficient of Performance– Power graph for AR 2, 4 thrusters

FEMTA- Test Results

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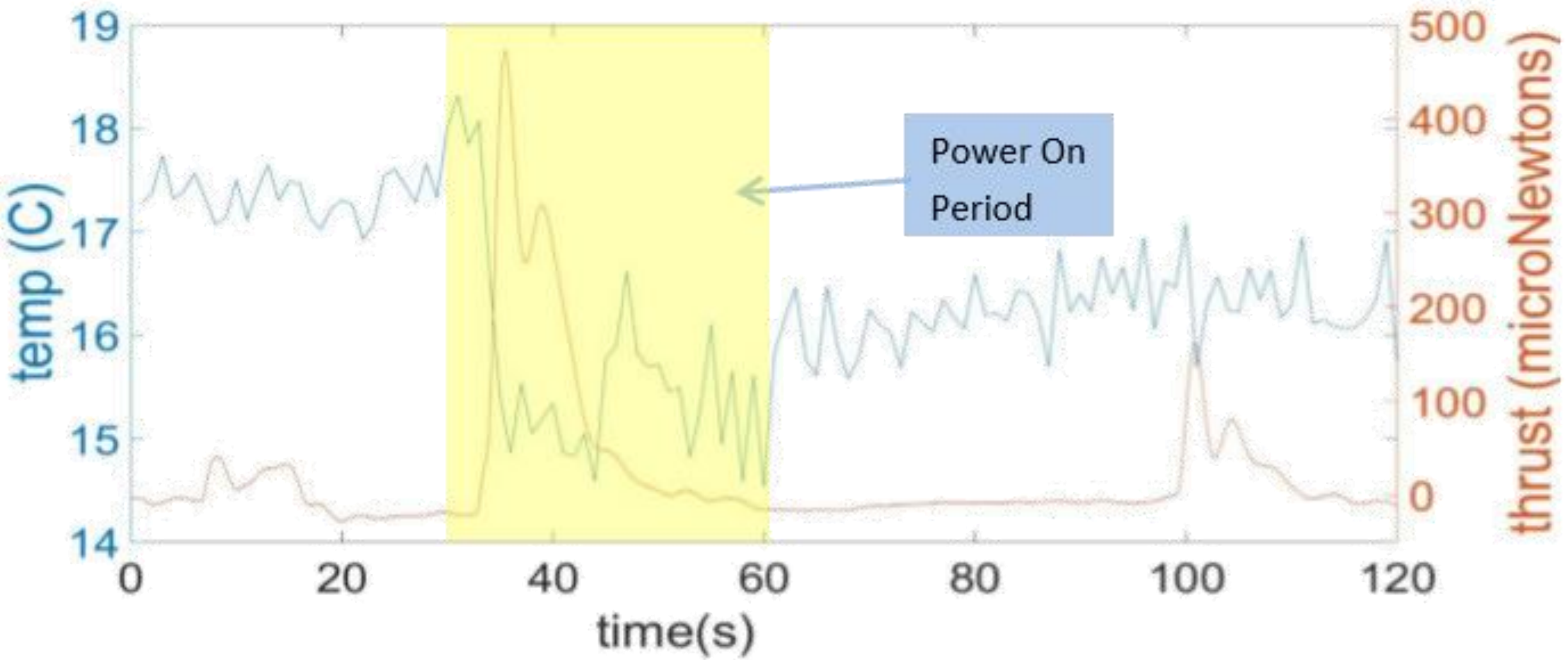
- Unwanted impulse bits have occurred at random as seen near the 100 second mark.
- These appear to be caused by outgassing in the fluid and provide no sustained thrust and no discernible cooling effect suggesting expulsion of water droplets caused by bubble formation due to the low back pressure.
- This problem seemed to be eliminated in the higher aspect ratio models.



Thrust and temperature history showing switching

FEMTA- Test Results

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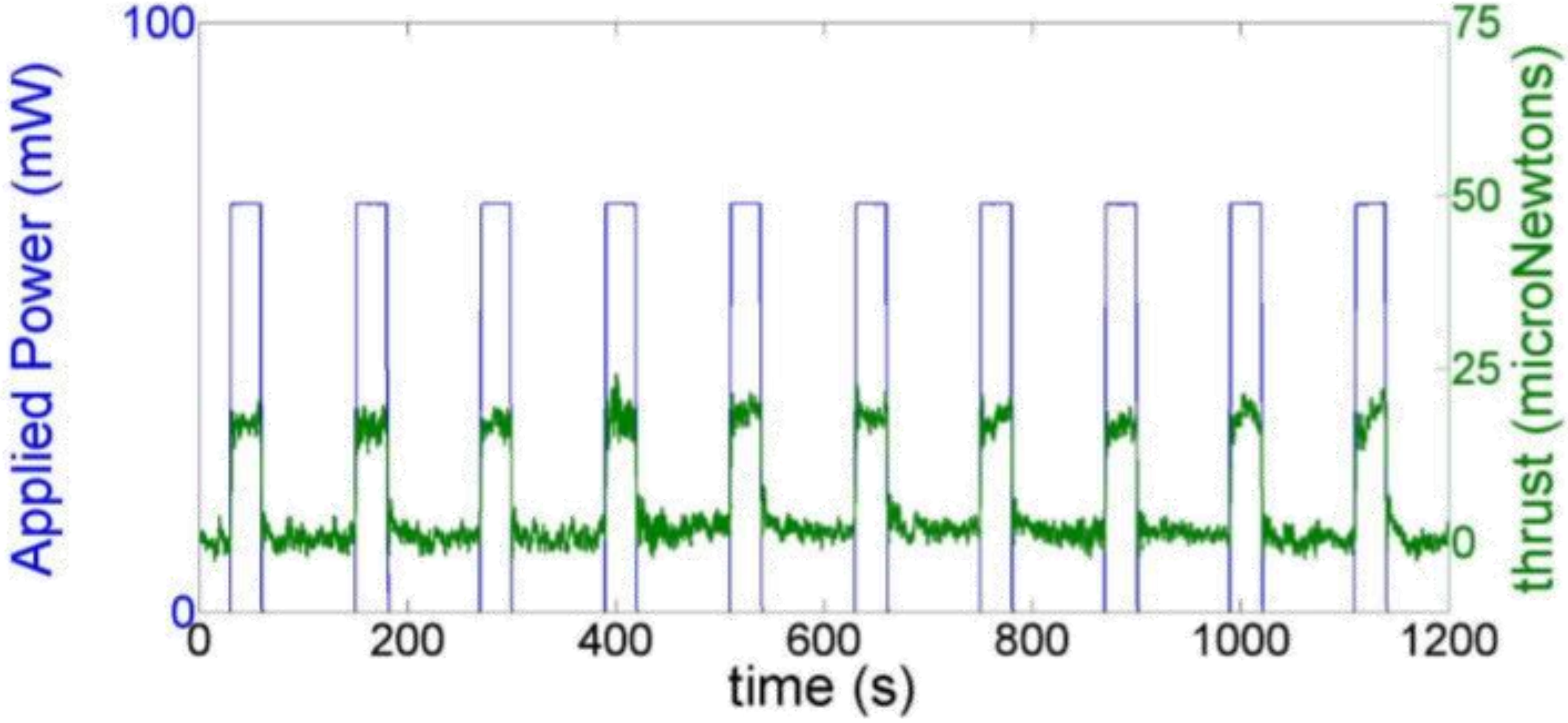
- A series tests were performed on one of these consisting of ten pulses of equal power of 30 seconds in duration and separated by 90 second delays
- Stability and response of the system was enhanced but with a loss of thrust and a reduction of the cooling effect



Thrust and power history showing switching cycle

FEMTA- Simulation

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- Modelling of the FEMTA thruster is divided into two areas:
  1. Continuum heat transfer and liquid flow simulations
  2. Direct Simulation Monte Carlo (DSMC) simulations of the vapour flow

- An iterative scheme is used to couple the two regions. The heat transfer in the liquid phase portion of the thruster was modelled using COMSOL. A geometry that represented the thruster and incorporated both the Joule heating from the Platinum heaters and the heat flux from evaporation was simulated.

- The results of modelling show similar magnitudes of thrust between the simulated and experimental data but have different trends in terms of the relationship of power and thrust. The modelling under predicts the thruster performance.

- The main reasons for the discrepancy between current modelling and experimental measurements are non-continuum fluid and thermal effects at the liquid-vapour interface.

Conclusions

John Sebastian

- The device proposed here uses the effect of surface tension on a microscale hydrophobic surface to contain liquid under vacuum conditions.
- Vapour flow is thermally controlled hence no moving parts or actuators are needed to provide thrust in the microNewton range for station keeping or attitude control.
- The heat of vaporization is drawn from the bulk fluid which provides a cooling effect as waste heat may be used to replenish it
- The FEMTA concept could provide a low mass, low power and high thrust propulsion alternative for pico and nanosats requiring no high pressure tanks, valves, high voltages, or large power supplies.
- The Isp is on a par with cold gas systems without the complexity or mass.
- The propellant is ultrapure water eliminating cost and danger associated with some other propellants such as hydrazine.
- Higher aspect ratio devices revealed improved controllability and repetitive operation but with decreased performance.

References

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