Ultracompact Microthruster for Pico/Nanosat Attitude and Thermal Control based on Film-Evaporation Effect

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ABSTRACT

There are no mature technologies currently available for tunable propulsion and precise attitude control for picosats without sacrificing a substantial mass fraction of the spacecraft. Although MEMS-based liquid and solid chemical as well as electric thrusters have been developed previously, the miniaturization of the valve and power processing components remains a significant challenge. Here we present development and demonstration of the micorscale tunable thermal valve for micropropulsion and thermal control aimed at achieving extremely small system size down to less than 1/100 U.

This paper reports a miniaturized thruster for nano, pico, and femto class space vehicle propulsion and thermal control which can be contained within as small as 2 cm³ volume including 1 gram of propellant. Electrical requirements can be 5 Volts or less with power draw in the tens to hundreds of milliwatts. The film-evaporation concept exploits the microscale effects of fluid surface tension and hydrophobicity and heat transfer enabled by advanced microfabrication techniques to improve the system size as well as the thrust-to-power performance.

INTRODUCTION

A space born vehicle is generally only useful as long as position and orientation can be controlled. Angular momentum can be adjusted by reaction wheels but in a constant torque situation these quickly reach their operational limit and must be desaturated with either a microthruster or a magnetorquer if an ambient magnetic field is present. However miniaturized mechanical technology has not kept pace with electronics due to microscale effects such as viscosity, surface tension, and stiction, thus microthruster performance does not scale down linearly with mass. Various electric propulsion systems have been designed and implemented but all suffer from excess power consumption and bulky power processing units needed to produce either high voltages or high currents. Many require long start up times so that fast response is difficult. There are currently no commercially available propulsion systems that can be integrated into a 1U cubesat that does not require less than 10% of the mass or volume budget and consumes less than the 1 of Watt power usually allocated for propulsion of this class vehicle. The concept for the Film Evaporation MEMS Tunable Array (FEMTA) described here was created as a response to this deficiency. A visualization of a proposed three axis control system incorporating these thruster scan be found in Figure 1.

CONCEPT

Figure 1: Rendering of 12 FEMTA units positioned for 3-axis control on a 1 U cubesat in low Mars orbit (top); closeup of 10 X 10 thruster array (bottom left); closeup of individual nozzle (bottom right)
FEMTA operation utilizes the microscale effects of surface tension and hydrophobicity to balance with stresses created by temperature dependent vapor pressure, as illustrated in Figure 2, and is loosely based on inkjet technology[1]. A critical size of capillary for 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

\[ d = \frac{\pi \cos \theta}{\rho_{vap}} \]  

(1)

where \( d \) is the gap size of the annular or slit capillary, \( \tau \) is the surface tension, \( \theta \) is surface contact angle, \( \rho_{vap} \) is vapor pressure which depends exponentially on the temperature of the liquid film. Specifically for water the critical gap size varies from \( d=60 \mu m \) to \( 10 \mu m \) for film temperatures from 20 to 50 °C as plotted in Figure 3. 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 for individual elements in the FEMTA array. No moving parts or high pressure is required so the system volume is orders of magnitude smaller than for those with the state-of-the-art proportional (e.g. solenoid) valves. The film-evaporation valve can be directly embedded on the micromachined propellant storage container. Because the physical effect of the thermal valving is on the micrometer scale, individual thrusters must be sized accordingly. Multiple elements are used to provide the desired maximum thrust. This also augments minimum impulse control and provides a redundancy feature in case of failure of one or more elements.

Performance for this device was estimated using ideal isentropic conditions and the assumption that the ejected fluid was vapor only. The mass flow \( \dot{m} \), with critical temperature set at 50 C can then be calculated as

\[ \dot{m} = \frac{W}{C_p \Delta T} = 7.97 \text{ mg/s} \]  

(2)

Where \( W \) is available power, \( C_p \) is specific heat, and \( T \) is temperature. Heat of vaporization is drawn from the bulk fluid. The cooling rate can be found by

\[ P = \dot{m} h_v - W = 17.5 \text{ Watts} \]  

(3)

In non-cooling mode, which might be needed in a dark space environment, the vaporization energy can be replenished by a substrate heater. With a fixed power limit of 1 W this could reduce continuous mass flow to

\[ \dot{m} = \frac{W}{C_p \Delta T + h_v} = 455 \mu g/s \]  

(4)

Where \( h_v \) is heat of vaporization. If a pulsed mode is used the heat could be replenished between firing times so that performance would not be diminished. The specific impulse is approximated using the formula for a converging nozzle

\[ Isp = \frac{\sqrt{R_T \gamma + 1}}{g} = 73.7 \text{ s} \]  

(5)

Where \( R \) is the specific gas constant, \( \gamma \) is ratio of specific heats, and \( g \) is gravitational acceleration. Assuming the flow exists at sonic speed the exhaust velocity would then be

\[ \sqrt{R T} = 445 \text{ m/s} \]  

(6)

Assuming the ideal Isp will produce a thrust of
\[ F = m g \cdot I_{sp} = 5.7 \, mN \text{ cooling mode} \]
\[ = 329 \, \mu N \text{ non-cooling mode} \]  

A single FEMTA unit with a 1 g propellant can also provide an approximate delta-V of

\[ \Delta V = I_{sp} \cdot g \cdot \frac{m_p}{m_s} = 0.72 \, \frac{m}{s} \]  

for a 1 kg spacecraft in a 160 km LEO where \( m_p \) is mass of propellant and \( m_s \) is the mass of the spacecraft. By rearranging the equation for orbital velocity

\[ V_0 = \frac{\mu}{\sqrt{a_0}} \]  

where \( a \) is the orbital radius and \( \mu \) is the standard gravitational parameter for Earth so that

\[ V_0^2 \, a_0 = V_t^2 \, a_1 \]  

an altitude change can be calculated as

\[ \Delta a = a_0 \left( \left( \frac{V_0}{V_0-\Delta V} \right)^2 - 1 \right) = 1.2 \, km \]  

**PROTOTYPES**

Fabrication of FEMTA units began in Fall 2013[2] and was performed in the clean room facility of the Birck Nanotechnology Center at Purdue Universities discovery Park. An axisymmetric plug annular nozzle was the original design but had to be altered due to the complexity of fabrication and the difficulty of aligning the plug inside the exit to within micron tolerances. A 2D rectangular nozzle was adopted (see Figure 4) instead with a critical throat width of 10 microns to set firing temperature at 50° C and a length of 2.5mm such that a length to width ratio of 250 would allow simpler 2D modeling. Throat depth was varied at 20, and 80 microns to provide aspect ratios (AR) of 2 and 8 (see Figure 8) respectively. The nozzle inlet angle was set by the anisotropic wet etch angle of silicon at about 55 degrees. The inlet depth was limited to 25 microns as the maximum depth that a repeatable photolithography could be performed, which required an inlet width of 40 microns. To date three generations of thrusters have been fabricated with consistent inlet and throat geometries but differing in exit configuration, substrate thickness, and heater material. Schematics was limited to 25 microns as the maximum depth that a repeatable photolithography could be performed, which required an inlet width of 40 microns.
First Generation Devices – Gen 1

Nickel-Chrome alloy (nichrome) was chosen as the heater material because of its availability, malleability, low cost, and resistance to oxidation. However when power was applied to the heaters voids appeared in the film as can be seen in the SEM image in Figure 6. This was originally attributed to electromigration caused by excessive current density[3], a second generation fabrication was initiated to reduce this.

Second Generation Devices – Gen 2

The failures of all Gen 1 heaters under extended electrical loading required a second fabrication to be initiated. The heater thickness was doubled to reduce cross section current density by a factor of 1.4 to eliminate electromigration as a failure mode and the insulating oxide layer thickness was increased 4 fold to reduce power loss due to thermal diffusion into the substrate. Enhancement of the heater layer was achieved by increasing sputtering time of the nichrome deposition in the fabrication process. And was accomplished by altering the growth sequence in the furnace tube. The gold conductor layer was omitted to reduce fabrication time and complexity, because of the 300:1 ratio of the contact to heater width this only increased overall resistance around 1%. Two intermediate throat aspect ratios of 4 and 6 were produced by varying the depth of the exit channel to 40 and 60 microns. SEM photos of all four aspect ratios can be found in Figure 7.

Table 1: Variations in FEMTA design

<table>
<thead>
<tr>
<th>Model</th>
<th>Heater</th>
<th>Aspect Ratios (AR)</th>
<th>Heater Layer (µm)</th>
<th>Oxide Layer (µm)</th>
<th>Wafer Thickness (µm)</th>
<th>No. Produced</th>
<th>Yield (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen 1</td>
<td>Ni/Cr</td>
<td>2, 8</td>
<td>0.7</td>
<td>0.5</td>
<td>200</td>
<td>12</td>
<td>11</td>
<td>Immediate heater failure – evaporation tests only</td>
</tr>
<tr>
<td>Gen 2</td>
<td>Ni/Cr</td>
<td>2,4,6,8</td>
<td>1.4</td>
<td>1.9</td>
<td>200</td>
<td>8</td>
<td>7</td>
<td>Fast heater failure – Only AR ~8 models thrust tested</td>
</tr>
<tr>
<td>Gen 3</td>
<td>V</td>
<td>2,4,6,8</td>
<td>0.7-1.4</td>
<td>1.8</td>
<td>500</td>
<td>196</td>
<td>95</td>
<td>Gradual heater failure – non repeatable powered tests</td>
</tr>
<tr>
<td>Gen 3*</td>
<td>Pt</td>
<td>2,4,6</td>
<td>0.14</td>
<td>1.8</td>
<td>500</td>
<td>26</td>
<td>75</td>
<td>No heater failure – repeatable testing</td>
</tr>
</tbody>
</table>

*Reworked – Vanadium removed and replaced with platinum

Figure 6: Heater film destruction during powered test in an aqueous environment.

Figure 7: Nominal aspect ratios of Gen 2 nozzles AR ~ 2 (top left), AR ~ 4 (top right), AR~6 (bottom left), AR ~8 (bottom right).
The 200 micron wafers were found to be too delicate for the manual manipulation required for a prototyping fabrication. Spinning, developing, and wet etching require handling the wafers with tweezers which can cause breakage just with movement through the air and even more so through a liquid. Vacuum clamping in the spinner and mask aligner were also forceful enough to cause fractures. This resulted in many pieces having to be fabricated one by one leading to inconsistencies in heater production and throat centering within the inlet.

The chemical etching process for the nichrome heaters was found to be highly inconsistent because all etching solutions tried showed preference for either chromium or nickel. Component rich pockets that were deposited during the sputtering process increased the problem. This caused undercutting and irregular etching along some masked surfaces. The thicker heater layers did provide a few brief powered tests but were plagued by galvanic corrosion at potentials over 2.5 volts.

**Third Generation Devices – Gen 3**

The small batch yield and lack of consistent dimensions required yet another fabrication. The wafer thickness of the Gen 3 devices was chosen to be 500 microns due to availability and ease of handling. The internal nozzle design was consistent with both Gen-1 and Gen-2 designs with the greatest alteration being the width and depth of the exit channel (see Figure 5). Wet etching of the exit was prohibited by the lifetime of the oxide mask in the etching solution so Deep Reactive Ion (DRI) plasma etching was used instead. The heater material was changed from nichrome to vanadium to eliminate the wet etching problems described previously. Vanadium is resistant to strong sulfuric acid and seawater however it was found that deionized ultrapure water oxidizes it in a few hours and faster when current is applied. After several tests of limited duration it was decided to change the material to platinum.

**TESTING AND RESULTS**

Testing of FEMTA prototypes was performed at the Purdue High Vacuum Lab. A 22 liter clear acrylic chamber was used for Gen 1 testing has an ultimate pressure of 10 milliTorr and was used when higher vacuum was unnecessary. The limited volume also restricted instrumentation accommodation so experimentation was limited in scope. A 4.2 cubic meter stainless steel chamber was used for Gen 2 and 3 testing has an ultimate pressure of 1 microtorr and houses the microNewton torsional balance seen in Figure 8. This balance can measure forces down to 8 microNewtons with 3% repeatability[4].

Uncertainty errors for power, thrust, mass flow, and Isp were calculated using the Taylor series method[5] and are found in Table 2, thrust uncertainty remains constant above 72.7 µN.

![Figure 8: MicroNewton thrust stand mounted in vacuum chamber.](image-url)
Table 2: Uncertainty of measured variables

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Measurement Device</th>
<th>Repetitive Error</th>
<th>Measurement Error</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>DAQ</td>
<td>±1 LSB</td>
<td>±15 ppm</td>
<td>negligible</td>
</tr>
<tr>
<td>Thrust@8.7 µN</td>
<td>LVDT</td>
<td>±1.7%</td>
<td>±7%</td>
<td>±7.2%</td>
</tr>
<tr>
<td>Thrust@32.7 µN</td>
<td>LVDT</td>
<td>±0.4%</td>
<td>±3.5%</td>
<td>±3.5%</td>
</tr>
<tr>
<td>Thrust@72.7 µN</td>
<td>LVDT</td>
<td>±0.2%</td>
<td>±1%</td>
<td>±1.0%</td>
</tr>
<tr>
<td>Mass</td>
<td>Ion Gauge</td>
<td>±7.2%</td>
<td>±5.1%</td>
<td>±8.8%</td>
</tr>
<tr>
<td>Isp@8.7µN µN</td>
<td>Calculated / Chamber backpressure</td>
<td></td>
<td></td>
<td>±11.4%</td>
</tr>
<tr>
<td>Isp@32.7 µN</td>
<td>Calculated / Chamber backpressure</td>
<td></td>
<td></td>
<td>±9.5%</td>
</tr>
<tr>
<td>Isp@72.7 µN</td>
<td>Calculated / Chamber backpressure</td>
<td></td>
<td></td>
<td>±8.9%</td>
</tr>
</tbody>
</table>

**Gen 1**

Evaluation of Gen1 FEMTA models began in May 2014 with simple resistance measurement of the internal heaters. This particular sample was chosen because the throat was not etched through so it was not usable for flow tests but the heaters were operational. This provided the expected results of calculated heater temperature ~100 degrees Celsius when submerged in water. However extended powered duration caused increased permanent resistance resulting in premature failure.

Mass loss due evaporation while in quiescent or unpowered mode must be determined so that an accurate mission specific propellant budget can be devised. Tests have been completed and are presented here.

A polycarbonate test vessel pictured Figure 9 to which was added approximately 15 grams of ultrapure water. This was then weighed on an analytic scale before being placed in the vacuum chamber. This arrangement allows the back pressure on the nozzle to be controlled so that it would equal the vapor pressure of the water at that temperature plus the hydrostatic pressure of the water column in the vessel. A port was added to the top of the vessel to release air from during the pump down procedure and was closed at a preprogrammed setting.

The tests were carried out in acrylic vacuum chamber seen in Figure 8. Chamber pressure was measure by a 10 Torr Baratron 626, vessel pressure was measure by a 100 Torr Baratron 122, and bulk fluid temperature was measured with a T type thermocouple. All signals were routed through a NI pci-6229 DAQ and were processed and recorded by a Labview program.

![Figure 9: Test vessel for powered and unpowered evaporation experiments; CAD model (top left and center), assembled (top right), disassembled (bottom).](image-url)
A series of evaporative test measurements were performed in the acrylic vacuum chamber on AR~8 nozzles and plotted in Figure 10. The longer duration tests show an evaporation on the order of 20 mg per hour. One hour tests are shown in blue, 15 hour tests in red and a 48 hour test in black. This results in 29.9 ±15.5 mg/hr evaporation rate with 95% confidence. It is believed the reduction in mass loss over time is due to a reduced impact of losses occurring during initial pumpdown.

**Gen 2**

Limited thrust testing of Gen2 thrusters was performed in the 4.2 cubic meter vacuum chamber at Purdue’s High Vacuum Lab on the microNewton thrust stand pictured in Figure 8. The polycarbonate test vessel from the Gen 1 evaporation tests was modified to mount on the thrust stand. The device was rotated so that the nozzle exit would have the horizontal orientation needed for thrust measurement. The pressure relief port on the upper plate was plugged and a new one drilled and tapped in the cylinder body. A simple 0.5 psi pressure relief valve replaced the active internal pressure control system used on previous tests. A photo of the vessel mounted on the thrust stand can be found in Figure 11.

The thicker nichrome layer permitted testing at higher power levels than the Gen1 models but effective lifetimes of the devices were still limited to a few minutes. Electromigration was no longer considered a factor since the current density was a magnitude lower than the accepted limit of 1 x 10^6 amps/cm^2. The only models that survived more than a few seconds were the AR~8 with the highest aspect ratio and theoretically the lowest flow rate. Maximum thrust was measured well below one microNewton at all power levels indicating an extremely viscous flow which is expected in high aspect ratio channels.

Two tests were performed using a 7 Volt 100 hz square wave which provided 211 mW of applied power. Thrust histories of the first series are plotted in Figure 12 and indicate forces of less than 1 microNewton which are within the noise range. Another series of three tests at 431 mW were also performed and the results plotted in Figure 13 and show similar results.

The thrust to power ratios measured in these tests of around 1 microNewton per Watt would be too low even if it could provide Isp’s in the thousands of seconds as some electric thrusters.
The Gen 3 FEMTA thrusters were tested in a 4.2 cubic meter vacuum chamber using the microNewton thrust stand. A test vessel was fashioned from a 1 ½ x 1 ½ x 1 inch block of PTFE with power connections and a pressure relief port, Figure 14 contains a schematic and photo of this device.

The relief valve from Gen2 testing was used to reduce pressure from atmospheric to just above vapor pressure so that water would not be expelled during the pump down process. PTFE was chosen to replace the aluminum model used in earlier testing to reduce galvanic corrosion from metals having a dissimilar galvanic indices in an aqueous environment. Power to the device was provided by an Agilent E3649A power supply and controlled by the labview actuated relay used in the evaporation tests.

The platinum heaters eliminated the corrosion problems experienced with nichrome and vanadium so that a more comprehensive thrust testing format could be implemented. These heaters also operated at a lower voltage so that applied power could be controlled by a labview program with current augmentation from a unity gain power amplifier.

Testing of the vanadium film units revealed a common failure mode in the pressure relief valve which could stick open or shut during pump down on approximately 30% of the tests causing the water to either boil off when exposed to vacuum or be ejected from the nozzle. An active internal pressure control feature similar to what was used in the evaporation tests was added to alleviate this problem, this also permitted monitoring the internal pressure and to raise or lower it at will. Bulk fluid temperature was monitored by means of an amplified type-T thermocouple.

The only models tested with the vanadium heaters were of AR~2. The thrust history of a 65 mW test is plotted in Figure 15. The maximum thrust attained exceeded isentropic flow calculations through a throat of the same dimensions by a factor of two. This seemed to indicate that the flow through the nozzle throat was primarily liquid rather than vapor which was then vacuum boiled in the exit cavity. The total impulse was found by integrating thrust over time beginning at the start of the power pulse and continuing to the end of the test and totaled 12.7 mN·s.
These plots seem to indicate an extremum at around 50 mW when the Isp is highest but impulse to energy (or thrust to power) is lowest as there seems to be an inverse relationship between the two. The Coefficient of Performance or COP is a term used in air conditioning and is the ratio of cooling power to input power and can be applied here as the ratio of energy lost to vaporization to the energy input and is plotted against applied power in Figure 16 and mirrors the impulse to energy ratio. This is expected as the vaporization energy is provided by the bulk fluid rather than from the heaters.

Three AR–2 nozzles were thrust tested at different dates and varying power levels[6]. The resistance of the vanadium tended to increase over time so that constant or repeatable power levels were rare. A scatter plot of the Isps attained vs average applied power can be found in Figure 19.

The AR–2 tests with platinum heaters gave results similar to the earlier vanadium models in that thrust level and timing was erratic and unstable. The temperature histories of the single pulse tests verified the cooling effect the thrust and temperature histories of a 50 mW single pulse test are plotted in Figure 18, an unwanted impulse occurs before power is applied.

The temperature of 6 grams of water in the reservoir dropped about 1 degree Celsius over the course of the test. With the specific heat $C_p = 4.18 \frac{kJ}{kg \cdot K}$ this correlates to

$$\Delta E_{\text{liquid}} = m_{\text{liquid}} \cdot \Delta T_{\text{liquid}} \cdot C_p = 23 \text{ Joules} \quad (16)$$

of energy lost. Approximately 13 milligrams of water was ejected as vapor $m$. An energy balance can be expressed by

$$W = \Delta E_{\text{gas}} + \Delta E_{\text{liquid}} \quad (17)$$

Where $W$ is the energy added to the system and

$$\Delta E_{\text{gas}} = m \left( C_p \cdot \Delta T_{\text{gas}} + h_v \right) = 28 \text{ Joules} \quad (18)$$

is the energy change of the ejected mass with vaporization energy $h_v = 2.2 \text{ MJ/kg}$. This leads to $W = 5 \text{ J}$, the known input was 50 mW for 30 seconds or 1.5 J. The other 3.5 J can be accounted for by cooling of the walls of the test vessel.

To ensure this process is thermodynamically valid an entropy generation balance is used

$$\Delta S_{\text{gen}} = (S_2 - S_1)_{\text{liquid}} + (S_2 - S_1)_{\text{gas}} \quad (19)$$

$$(S_2 - S_1)_{\text{liquid}} = s^0_{\text{liquid}} \cdot \Delta T_{\text{liquid}} \cdot m_{\text{liquid}} = -23 \text{ J} \quad (20)$$

Where $s^0_{\text{liquid}} = 3886 \frac{J}{kg \cdot K}$ is the specific entropy change for liquid water. The entropy change for the gas

![Figure 16: Coefficient of performance vs applied power.](image1)

![Figure 18: Thrust and bulk temp histories for 30 second 50 mW pulse on Gen 3 AR–2 nozzle with platinum heaters.](image2)

![Figure 19: Specific Impulse vs applied power for Gen3 AR–2 nozzles with vanadium heaters.](image3)
has two parts; the change of the liquid to FEMTA firing temperature and the change from liquid to gas, and is given by

\[
(S_2 - S_1)_{gas} = m_{gas}(s_0^{\text{liquid}} + \Delta T_{gas} + \Delta s_{vap} \cdot s^0 \cdot T) = 43 J
\]  

Assuming the phase change occurred at \( T = 323 \) °K which is \( \Delta T_{gas} = 30 \) °K, and \( \Delta s_{vap} s^0 = 2.1 \frac{MJ}{kg K} \) is the specific entropy change of vaporization, then \( \Delta S_{gen} = +20 \text{ joules} \) so that the second law of thermodynamics is not violated though the exact thermal mechanism is yet to be ascertained.

Tests on an AR~4 nozzle provided more consistent results so that automated multipulse experiments could be conducted without unwanted mass flow or impulse bits between desired firing times. A series of tests consisting of 10 equally powered pulses of 30 second duration and 90 second delays were performed at 25, 50, 75, 125, 150, 200, and 300 milliWatts. The thrust and power histories of the 75 mW test are plotted in Figure 19. These compelling results show highly repeatable behavior with substantial thrust (when compared to prior attempts in Gen 1 and Gen 2 designs. Thrust was obtained only when commanded.

The power to thrust delay time is on the order of 200 milliseconds and show none of the delays and non-commanded thrust episodes displayed by the AR~2 models. This allows taking average thrust across the pulse instead of integrating over time as was done with the AR~2 tests. Thrust data for all AR~4 tests are plotted in Figure 20 and display a linear trend with power. The thrust to power ratio is plotted with the impulse to energy data from the AR~2 tests in Figure 21 and indicates that the AR~2 nozzles deliver an order of magnitude more impulse per energy input than the AR~4 nozzles. Isp’s

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Figure 19: Thrust and power history for 10 pulses at 75 mW and 30 second duration with 90 second spacing.

Figure 20: Thrust vs applied power for Gen3 AR~4 nozzle with platinum heaters.

Figure 21: Thrust/Power ratios for AR~4 and AR~2.

Figure 22: Comparison of Isp’s of Gen3 AR~2 and AR~4 nozzles with applied power.
for both types of FEMTA are plotted in Figure 22 and show that at applied power of 50 mW or less the AR~2 provide as good or better performance than the AR~4 reach a peak near the isentropic limit for a converging nozzle at around 50 mW. The nozzle design and FEMTA operation mode can be made mission specific to optimize whichever qualities are required whether thrust, Isp, or thermal control.

CONCLUSIONS
A propulsion system has been developed for potential application for control of nano and picosats. The device, which relies on capillary control of water within a micron-sized high aspect ratio nozzle, has been shown to deliver specific impulse over 80 seconds, a value that exceeds cold gas performance. The device is the only known capability to meet the volume and power demands of these small spacecraft with an overall volume of less than 2 cubic centimeters, a mass less than two grams and thruster powers less than 400 mW using an input potential of 2-5 VDC. Using a nozzle aspect ratio of four, stable and repeatable thrust values were measured and ranged from 6 µN at 25 mW of input power to 68 µN at 300 mW power level with an average thrust to power ratio of around 230 µN/W. The on/off response time was around 200 milliseconds. The low pressure liquid propellant storage means a much greater mass ratio than high pressure systems whose effective Isp might be a tiny fraction of that of the propellant.

Several iterations of microfabricated devices were to arrive at a suitable combination of throat aspect ratio and heater material for the current units. The fabrication process relies on standard MEMS processes and permits fabrication of 52 units on a single 4 inch wafer. Typical yields in the current process are 95%.

The evaporation of water that serves as thrust production mechanism also has benefit of providing cooling to the local structure. In the units with throat aspect ratios of two, cooling coefficients of performance as high as 11 have been measured. Unfortunately the thrust performance of the AR~2 units has proven to be unreliable due to meniscus instability leading to increased response times and uncommanded impulses. However, this intermittent performance has shown a greatly enhanced thrust to power ratio as much as 5 mN/W, an order of magnitude greater than AR~4, because more vaporization energy is extracted from the fluid. Further development is underway to define an optimal aspect ratio such that energy and propulsion efficiency can be maximized.

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References