CubeSat Microwave Electrothermal Thruster (CμMET)

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Mikhail D Abaimov,[1] Swarna Sinha[2], Sven G. Bilén,[3] and Michael M. Micci[4]
The Pennsylvania State University, University Park, PA 16802, USA

A CubeSat Microwave Electrothermal Thruster (CμMET) propulsion module is being developed in order to expand the mission capabilities of 3U-and-larger CubeSats. The MET uses microwaves to generate a plasma inside a resonant cavity, which is then used to heat the propellant that exhausts through a nozzle, generating thrust. The thruster being designed operates at a microwave frequency of 17.8 GHz at an input power of 10 watts. Work to date on the CμMET module has included requirements development, electromagnetic modeling, systems-level design, and component selection for packaging within a 1U or 1.5U module. This paper provides the current status of the design effort.

I. Introduction

MICROWAVE electrothermal thrusters (METs) operate by using plasma to heat up gaseous propellant and accelerate it via a nozzle, thereby creating thrust.[1] A schematic of the MET is shown in Fig. 1. The MET's operation is as follows. A plasma is created inside of a resonant cavity using microwave power. The microwaves enter the cavity via the antenna located at the bottom of the thruster head. A transverse magnetic TM^{z}_{011} mode forms inside the cavity, which concentrates the electric field at the antenna and nozzle ends of the cavity. Propellant is pumped tangentially into the cavity at the nozzle end and a vortex flow is created. With these conditions present, plasma ignites next to the nozzle. In order for ignition to take place, the cavity must reach pressures significantly less than atmospheric, but it does not need to be a high vacuum. After ignition, the pressure may rise while maintaining plasma. The plasma is self-sustaining and stabilized by the vortex flow, which also cools the cavity walls after ignition. The standing plasma heats any additional flow, thereby turning the cavity into a pressure chamber and producing thrust as heated propellant exits from the nozzle.

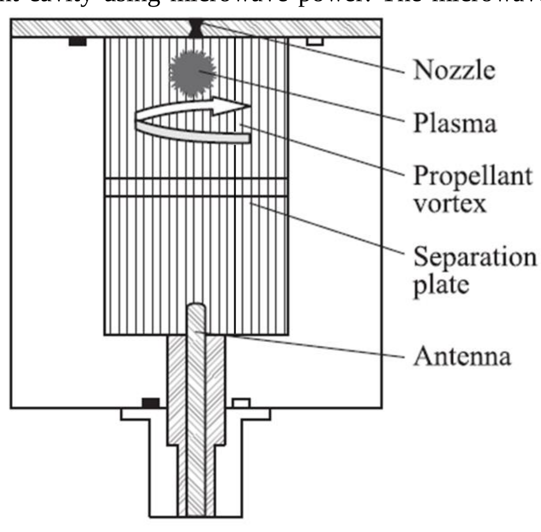

Figure 1. Schematic of MET.[1]

Research into METs at The Pennsylvania State University began in the 1980s.[1] The first version of the thruster operated at 2.45 GHz with an input power of 1 kW to 2.5 kW. This model had relatively large cavity dimensions of 15.75 cm in length and 10 cm in diameter and served to validate the MET concept. Subsequent versions of the thruster were designed to operate at 7.5 GHz, 14.5 GHz, and 30 GHz. The 7.5-GHz and 14.5-GHz thrusters were tested using a

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[1] Graduate Student, Aerospace Engineering, mda5099@psu.edu
[2] Undergraduate Student, Aerospace Engineering, currently Associate Engineer at UTC Pratt & Whitney, swarnasinha@gmail.com
[3] Associate Professor, Engineering Design, Electrical Engineering, and Aerospace Engineering, sbilen@psu.edu
[4] Professor, Aerospace Engineering, micci@psu.edu

number of propellants and were significantly smaller than the first model. The 30-GHz MET was the smallest; however, plasma ignition was never achieved with the 1-W microwave source available at the time, since calculations indicated >2–3 W were required for ignition.[2] Increasing resonant frequency between model iterations had the effect of decreasing the physical size of the thruster, decreasing the required input power, and increasing performance, all of which are very desirable qualities in small satellite propulsion.

The CubeSat picosatellite standard defines satellites designed to fit into cube-shaped units (U) of 10 cm per side.[3] Many universities, some high schools, and NASA and private industry have developed their own CubeSat missions since the standard's inception in 1999. These missions include atmospheric observations, radio communication experiments, photography, and technology demonstrations.[4] Due to their extremely small size, propulsion options are very limited. As such, CubeSat missions are currently limited in scope. In addition, CubeSats are sometimes criticized for their possibility of becoming "space junk" due to the inability to be properly decommissioned at the end of their useful lifetime. A propulsion system would allow for more mission flexibility and alleviate concerns about decommissioning.

An MET of sufficiently small size is a practical solution to providing propulsion capability to CubeSats. Solid rockets are less efficient and lack an ability to relight. Chemical rockets have complex plumbing and delicate components, which are generally not suited for small missions. Cold-gas thrusters are inefficient and do not provide enough change in velocity (delta-V) for extended missions. An MET with a cavity sized to resonate at 17.8 GHz offers a small size that will fit into a 1U module providing reasonable delta-V. It would also add a number of benefits, such as using a small amount of power and being able to operate using "green" propellants such as ammonia.

II. CμMET Design

The MET propulsion module is being designed to fit within a 1U or 1.5U volume. The propulsion module consists of several subsystems: (1) the MET thruster cavity; (2) a power subsystem that will manage power distribution to the MET components from the satellite's power supply; (3) a propellant subsystem that stores propellant and delivers it to the thruster on demand, consisting of a propellant tank, associated valves, and plumbing to the MET; and (4) a microwave source subsystem that produces and delivers microwave power to the resonant cavity, comprised of a microwave source, power amp, and cabling for power transfer. All components of the CμMET module must fit within a 1-liter (1U) to 1.5-liter (1.5U) volume and have a combined mass of less than 1.33 kg or 2 kg, respectively (note, more mass could be devoted to the CμMET as long as total CubeSat mass requirements are met). The thruster should also use no more than 50 W when firing, which is currently the maximum that an advanced CubeSat solar panel driven power system can provide. In addition, the module must provide >500 m/s delta-V to maximize mission capability. CubeSat designers generally try to employ commercial-off-the-shelf (COTS) components when possible, so this philosophy was also followed with the CμMET design.

A. Cavity Design

The thruster's resonant cavity is cylindrical in shape, with resonant frequency, electromagnetic mode, and height-to-radius ratio dictating the cavity's dimensions. The input microwave energy must drive a TM^z_{011} mode for proper functioning. Adjusting the height-to-radius ratio at a given frequency drives the concentration of the microwave energy such that it is maximized at the cylinder's ends, one of which contains a nozzle and the other the antenna. In most MET designs, a dielectric cap is placed over the antenna or a dielectric plate at the midplane of the cavity. The cap or plate lowers the cavity's resonant frequency, but prevents plasma from forming near the antenna. The 14.5-GHz and 30-GHz MET were tested with caps and no dielectric, respectively. These models demonstrated good performance with a height-to-radius ratio of ~3.5.[5] Models designed to incorporate a dielectric plate, such as the 2.45-GHz and 7.5-GHz MET, had ratios of ~3.

For the case of the 17.8-GHz thruster, calculations yielded a cavity radius of 6.8 mm, accounting for a dielectric plate. Using COMSOL Multiphysics simulations, the optimum height was found to be 21.1 mm, yielding a height-to-radius ratio of 3.1.

1. Thruster Antenna Design

Antenna selection is very important in MET design because it affects the resonant frequency as well as electric field intensity. The electric field intensity depends on microwave power coupling, which in turn depends on antenna dimensions and shape. Due to the size limitations of the cavity, and a desire for commercial-off-the-shelf (COTS) availability, the possible antennas include SMA, SSMA, and 2.4-mm "candle-stick" bulkhead connectors.[2] Figure 2 shows how antenna type affects electric field intensity and resonant frequency in the cavity.

While the smaller antennas produced higher field intensities, the resonant frequency range was also much smaller. A smaller frequency range means that the power provided by the source has to be closely matched to the cavity's resonant frequency. COMSOL Multiphysics results also showed that smaller antennas produced higher field intensities close to the end plates of the resonant cavity, which is the most desirable condition for plasma ignition. These simulation results are illustrated in Fig. 3.

Since the 2.4-mm antenna showed the highest field intensities, its shape was investigated as well. The variations included a flat tip flush with the cavity surface, rounded tip flush with the cavity surface, a flat tip protruding 0.5 mm into the cavity, and a rounded tip protruding 0.5 mm into the cavity. In general, the flush antenna variations produced stronger electric fields than the protruding antennas. In addition, the flat tip produced a stronger field, while the rounded tip allowed for a less sensitivity in resonant frequency.

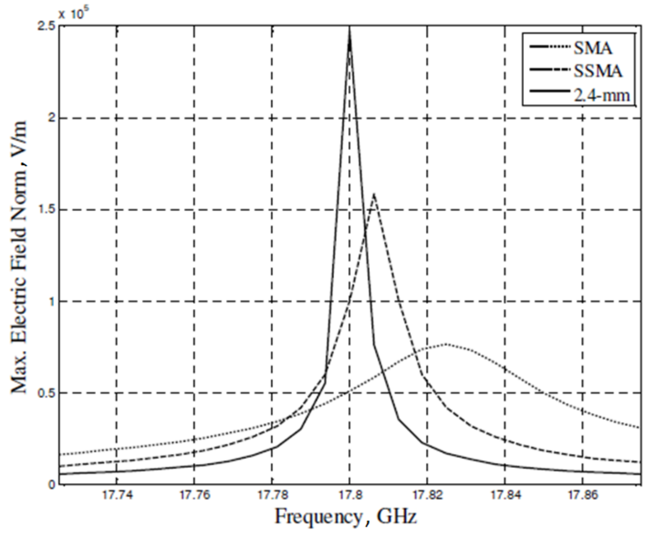

Figure 2. Frequency Sweep of the electric field strength for the SMA, SSMA, and 2.4-mm antennas.

B. Power System Design

The power subsystem distributes the power allocated by the satellite to the CμMET module. As mentioned above, we have set the maximum available power to 50 W. Components requiring power include the microwave source, power amp, and propellant valve. In addition, this subsystem must be able to handle any power-related issues, such as overcurrent.

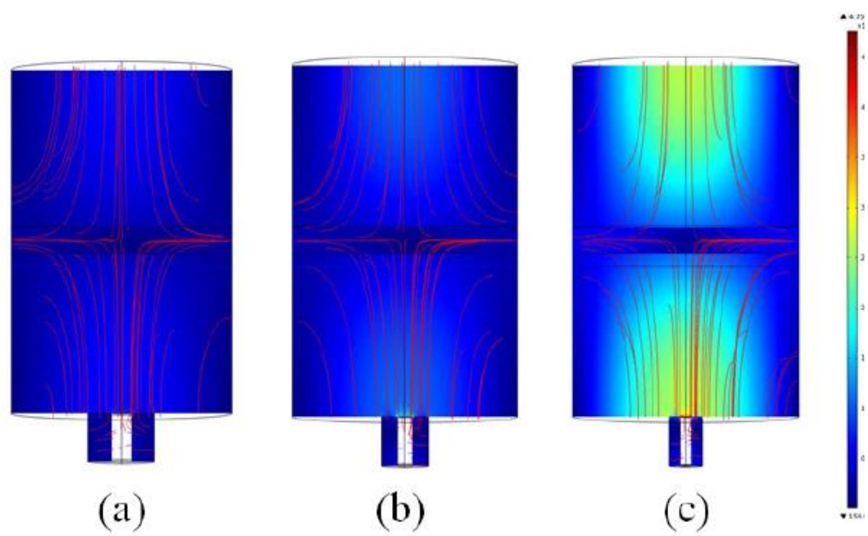

Figure 3. Electric field magnitude (V/m) contour plot and field line plot at 17.8 GHz for (a) SMA, (b) SSMA, and (c) 2.4-mm antenna.

C. Propellant System Design

An inherent advantage of the MET is its ability to utilize a variety of propellants. For the CμMET module the research focus is ammonia, which can be stored as a liquid under relatively low pressure, allowing more propellant to be stored than if a gas were used. Ammonia is also considered a "green propellant," which means that the propellant and its byproducts have low toxicity. This also greatly simplifies ground processing.

We desire a COTS valve for flow control in the propellant subsystem. Due to size and power limitations, a miniature or sub-miniature solenoid valve will have to be used, such as the A-series valve from Gems S&C.[6] In addition, the use of ammonia as propellant necessitates the use of a filtration or evaporation system to ensure that liquid-stored propellant reaches the resonant cavity in a fully gaseous state. Previous NASA projects utilizing ammonia propellant relied on capillary tube feeds for vaporization, but volume limitations of a CubeSat prevent a similar system from being used at the CubeSat scale.[7]

The propellant subsystem stores ammonia in a liquid state in a propellant tank designed to maximize the available volume. Current designs include rectangular tanks that maximize volume available in the CubeSat. Due to the temperature variation expected on a typical CubeSat mission, the pressure inside the tank may reach a maximum of 360 psi.[8] Finite element analysis using COMSOL Multiphysics were done on early tank concepts in order to ensure they would hold pressures up to 500 psi. Due to the potential corrosiveness of ammonia and yield strength requirements, it is preferred that all related components are made out of ferrous alloys or titanium. Copper and zinc-containing alloys are especially vulnerable.[8] Previous experiments demonstrated that an MET using ammonia as propellant can achieve a specific impulse (I_{sp}) of at least 550 seconds.[9] Assuming this performance figure, a 1U propulsion module can contain a tank with 350 cm^3 of volume, which translates to 311 m/s delta-V. If the module is allotted 1.5U within the CubeSat, the tank can be expanded to 750 cm^3. This larger volume allows for 692 m/s delta-V.

D. Microwave Power Source Design

The component selection process for the microwave source subsystem was complicated because the frequency, power, and efficiency requirements are very demanding due to the small available volume. However, we have identified a custom component consisting of a combined microwave source and power amplifier from Erzia Technologies S.L.[10] The component offers a good benchmark for further development. Power transmission to the cavity can be accomplished through a coaxial cable.

Using the current selections for all subsystems and preliminary propellant tank designs, a mockup of the entire module is shown in Fig. 4.

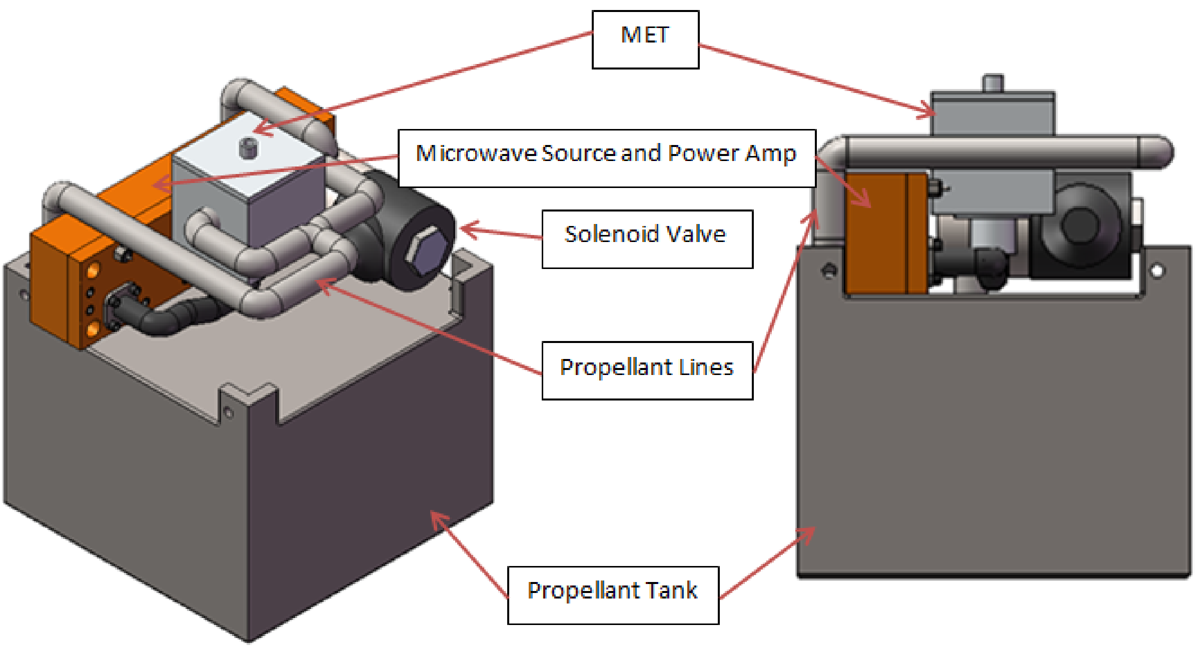

Figure 4. 3U CubeSat MET module concept.

E. Operation Overview

A CμMET would be used when the mission requires thrust for altitude change of the CubeSat. The main source of power on a CubeSat comes from its solar panels, so it is desirable to maximize the satellite's exposure to the sun, especially when the thruster is in use. Operation is also possible when in Earth's shadow by using onboard energy storage such as batteries. The thruster operates along a single axis and, therefore, would need additional attitude control to orient the CubeSat such that the thruster fires in the desired direction.

III. Summary and Future Work

We reported here on the preliminary design and simulation of a 17.8-GHz microwave electrothermal thruster that would work on a CubeSat platform. Calculations and COMSOL Multiphysics simulations yielded a resonant cavity with a 6.8 mm radius and 21.1 mm length. Further simulations showed that a commercially available 2.4-mm antenna with a flat, flush tip generated the strongest electric fields, which are most suitable for plasma ignition within the cavity. Early CμMET module design efforts yielded a concept of operation and the necessary module configuration. Suitable components of each subsystem were selected. Although the component choices are not final, they serve as a baseline for further refinement of the concept.

The concept is still in early stages, so much work remains. With cavity and antenna simulations complete, a physical thruster head can be constructed and tested under laboratory conditions. More research on the system components remains to be done, including investigating component alternatives and evaluating their performance. Propellant tank design is currently very basic, so further design work needs to be done before a physical model can be created and tested. After the individual components have been investigated, the next step would be to assemble the module. This complete module can then be tested before being implemented on a 3U CubeSat.

Acknowledgments

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