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CubeSat Electrothermal Plasma Micro-Thruster: System Development and Integration

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"The word [propulsion] is derived from two Latin words: ***pro*** *meaning before or forwards and* ***pellere*** *meaning to drive.* ***Propulsion*** *means to push forward or drive an object forward."* –NASA Glenn Research Center

ABSTRACT

Amid growing demand to expand CubeSat mission capability, several propulsion devices have been proposed for use in nanosatellites. One device, a scalable electrothermal plasma thruster named Pocket Rocket, has been researched and designed as an inexpensive and high-performance propulsion solution. A full integration of two Pocket Rocket thrusters into a 1U CubeSat form factor for spin maneuver testing has been completed, including Argon propellant storage, pressure regulation, an RF power and thruster controller, and a complete modular support structure. This prototype module was completed and tested in an environmental vacuum chamber to ensure space-capable operation, with future plans to complete a space mission to demonstrate the full potential of Pocket Rocket. Results show that the full assembly fits together inside the 1U CubeSat form factor and that the thrusters can be controlled individually. The burn time using the current proof of concept model is approximately 3 hours with an ion number density in the plume of approximately 2 x 10^{15} showing that the thruster is scalable from previous Pocket Rocket thruster tests and that the performance was not affected by the CubeSat integration of the thruster.

INTRODUCTION

CubeSats, 10 cm cubic modular satellites, provide an efficient and low-cost opportunity for space exploration and technological advancement. The use of CubeSats has become increasingly popular and the number of missions sent into space each year is growing exponentially. Today, hundreds of CubeSat missions have been successfully launched into orbit [1,2]. As the technology develops, so do the mission capabilities. Advanced science missions are now being attempted and planned [3].

Advanced CubeSat missions require the addition of micro-propulsion systems for attitude control, orbit adjustments, and extended mission lifetimes. In addition, the requirement that all satellites must de-orbit within 25 years of their end of life [4] means that CubeSat missions planned for higher orbital altitudes must contain de-orbit propulsion or other devices. Propulsion systems, however, can be hard to implement and can significantly increase costs. A thorough review of several CubeSat propulsion systems has been performed by Lemmer [5]. In contrast, this paper will focus specifically on the development of an electrothermal plasma micro-thruster known as Pocket Rocket.

Pocket Rocket, originally developed at the Space Plasma, Power and Propulsion Laboratory at The Australian National University, is a radio-frequency (RF) electrothermal plasma micro-thruster that uses RF power to initiate ion discharge of a propellant gas [6]. The Pocket Rocket thruster utilizes RF signals at 13.56 MHz applied to an annular antenna to produce a capacitive coupled plasma (CCP) within a dielectric discharge tube. Charge exchange collisional heating between ions and neutrons within the thruster tube creates gas temperatures around 1000 K and causes gas expansion and acceleration resulting in thrust [7,8]. Nominal power is between 5 and 10 W; however, experiments have been performed up to 60 W [6,8].

Further research and development on the Pocket Rocket thruster has been performed at California Polytechnic State University, San Luis Obispo (Cal Poly SLO) to provide a packaged propulsion system that can be integrated into any CubeSat mission. This paper will lay out the design aspects and challenges of the integrated system as well as key performance aspects. The integration of this thruster includes a gas delivery and pressurized storage system, a power delivery system, two independently controlled thrusters for thrust and spin testing, and a standard 1U CubeSat structure. When pressurized to the on-board pressure vessel standard for

CubeSat flight missions of 30 psi, the Pocket Rocket thruster has a total burn time of approximately 3 hours with a predicted force of approximately 1 mN [9].

SYSTEM OVERVIEW AND DESIGN

All subsystems have been designed to work together and to conform to the 1U CubeSat standard revision 13 [10]. The Pocket Rocket thruster is a cylindrical thruster with an outer diameter of 25 mm. The thruster is 35 mm long and weighs approximately 0.06 kg. A cross-sectional view of the thruster in given in Figure 1.

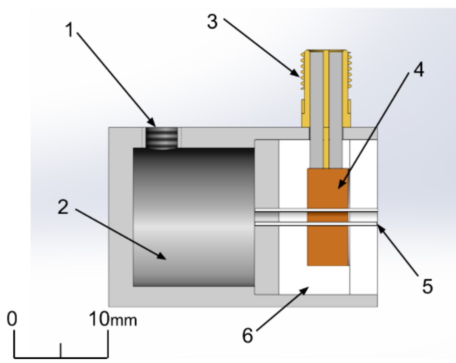

Figure 1: Pocket Rocket thruster section view detailing the internal component of the thruster.

Gas flows through the inlet of the thruster (1) into the plenum tank (2). The plenum tank creates a constant stagnation pressure at the back of the thruster to increase the thruster's overall performance and efficiency. Radio frequency signals at 13.56 MHz are delivered through a standard SMA-f connected antenna (3) and are delivered to the annular copper electrode (4) which couples the RF energy into the gas initiating the plasma breakdown. Running through the center of the thruster is an alumina tube (5) with an inner diameter of 3 mm. The alumina allows for insulation of the plasma, increases secondary electron emission [4], and helps to distribute the natural heat of the ions to the propellant gas. The aluminum shell of the thruster acts as the grounded electrode to complete the circuit. An insulating Macor cup (6) surrounds the copper electrode and electrically isolates it from the grounded aluminum housing.

The dielectric (Alumina) tube and Macor housing limit the flow of heat from the 1000 K propellant gas inside the discharge tube to the outside of the thruster housing and into the satellite structure [11].

Neutral propellant, usually argon, is fed into the plenum through the gas storage and regulation system. The RF power is supplied to the thruster electrode from a DC-RF converter that nominally runs off 4 V from the satellite mains [9]. However, for this proof of concept design, power sent to the thruster came from an external power supply that was passed through into the vacuum chamber. Figure 2 shows a simplified block diagram schematic of the complete Pocket Rocket system.

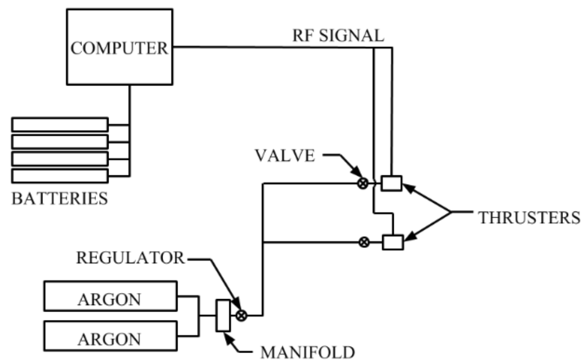

Figure 2: Pocket Rocket system block diagram showing how each subsystem works together.

The RF power must be coupled into the propellant gas at a sufficient voltage to induce plasma breakdown. Plasma breakdown occurs at a specific voltage for a given pressure-distance (p-d), as indicated by the Paschen breakdown voltage (V_b) curve for Argon shown in Figure 3. For Pocket Rocket, the pressure-distance criterion is the product of the gas pressure inside the discharge tube and the distance between the electrodes. The Pocket Rocket thruster has been designed to operate near the Paschen minimum for argon of 0.8 Torr-cm, which corresponds to plenum pressures between 0.5 and 5 Torr.

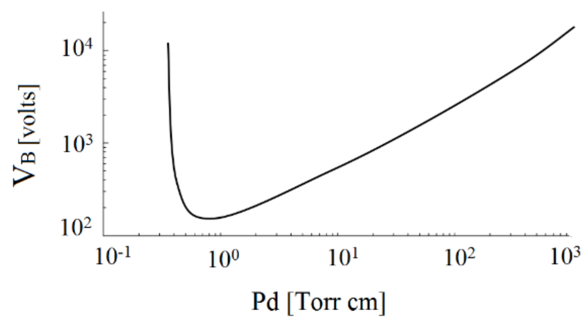

Figure 3: Argon Paschen curve for plasma breakdown voltages at a given pressure diameter (P_d) factors.

Gas Storage, Regulation, and Delivery

Pocket Rocket can use a variety of gaseous propellants including Argon (Ar), Nitrogen (N_2), or Carbon Dioxide (CO_2), [12] but operates best with argon due to the higher gas temperatures attained [7]. The gas storage and delivery system has been designed to easily integrate any propellant into the system by utilizing off the shelf gas cylinders. The cylinders have an outer diameter of 20 mm and are approximately 80 mm in length with an internal volume of approximately 14,000 mm^3. The gas cylinders can be manually filled through a port at the top of the manifold block to the desired storage pressure for the mission. Figure 4 shows the individual components of the gas storage system for the Pocket Rocket thruster.

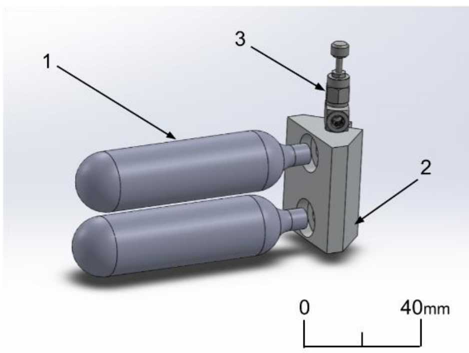

Figure 4: Gas storage tanks and manifold block design used for the Pocket Rocket system.

The storage system consists of two gas cylinders (1) that thread into the manifold block (2). The manifold block secures to the structure of the CubeSat using standard 2-56 socket cap screws to constrain one end of the gas tanks. Off the top of the manifold block is the manual valve (3) that allows for filling or bleeding off the gas stored in the cylinders. Once the gas is at the desired pressure in the manifold block, a locking nut on the valve stem can be secured down to ensure that the valve does not move during testing and flight missions.

The biggest challenge with the gas delivery system is designing a system that can regulate the flow and maintain pressures needed to operate the thruster. Pocket Rocket operates between 0.03-0.09 psi (0.5-5 Torr). As for the inlet pressure from the gas storage tanks, the current standard for an on-board pressure vessel for CubeSats is 29.4 psi (1500 Torr). This means that at the maximum pressure allowed in the storage tanks the system needs to regulate a pressure drop of 0.1% of the original pressure inside the tanks.

An additional challenge was introduced by the size limitation and pressure requirement of the pressure regulation system. Given that pressure and area are inversely proportional, a relatively low-pressure regulation generally requires a larger diaphragm area.
The solution was to find a regulator at the size requirements needed and then to further drop the pressure past the regulator via losses in the system. With the current design, a 0.009 *in* orifice plate is installed on the outlet of the regulator. The pressure is then further decreased through frictional losses through a series of flexible tubes contained in the system. The system uses Beswick Engineering's PRD3 regulator which is shown in Figure 5 [13].

Overall, the regulator is approximately 1.15 *in* tall with a diameter of about 1.00 *in* and weighs about 0.02 kg. The pressure regulator used in the Pocket Rocket system is a two-stage diaphragm regulator. The non-venting regulator references the surrounding pressure through the open ring at the top of the regulator. This is beneficial because the regulator can be calibrated to the desired outlet pressure in atmospheric pressure conditions and hold the required absolute pressure when introduced to the vacuum environment. There are also advantages to using a two-stage regulator. For example, a two-stage regulator can handle much higher inlet pressures than its single-stage counterpart. The model used in the Pocket Rocket system has a maximum inlet rating of 500 psi (26000 Torr). One other advantage is its ability to maintain a constant, steady outlet pressure past the regulator as the inlet pressure from the storage tank decreases. The regulator used in the Pocket Rocket system maintains a constant outlet pressure of 0.2 psi for a decreasing inlet pressure down to 5 psi. Other models such as the PDR3HP are 3 stage diaphragm regulators which allow a maximum inlet pressure rating of about 3,000 psi. Regulators such as this provide options for regulating pressure when the mission requires a greater volume of fuel. Both Regulators offer a variety of inlet and outlet connections, making assembly adaptable to the gas system needs [13].

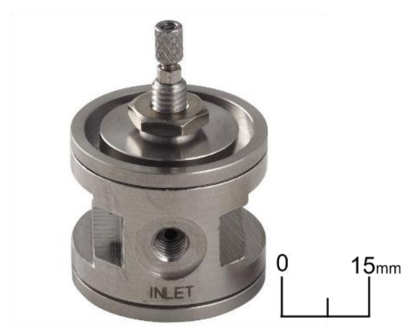

Figure 5: PDR3 pressure regulator from Beswick Engineering used in the Pocket Rocket gas delivery system [13].

The final goal of the gas delivery system is flow control. To control the satellite during flight, it is vital that each of the on-board thrusters be operated independently. This allows for control over both the rotation and translation of the satellite.

To allow operation of each thruster, a set of Lee Company valves were installed into each separate gas feed line from the regulator. The valves are three-way valves which allow gas delivery to the thruster upon a given supply voltage. The valves serve a dual purpose in the flow control system. First, the valves allow for individual control of each thruster to provide the satellite with precise maneuverability and control. Second, the valves allow for pulsing the gas delivery to align with the RF energy. To increase efficiency, a pulsed RF signal can be sent to the thruster. To better control the efficiency of the gas used, a feedback can be sent to the valve that allows it to sync the gas feed with the pulsed signals to the thruster. This will decrease the overall fuel consumption and allow for longer burn times and greater thruster performance.

Power and control of the valves and the thrusters come from the on-board power delivery system, which is provided by a BeagleBone Black microcomputer.

Power Storage and Delivery System

Power to all on-board electronic systems is supplied by 4 commercial sized 18650 lithium ion batteries. These batteries are to provide power to the satellite system board, the BeagleBone microcomputer, and the DC-RF converter used to operate the thrusters.

The system board was not included in this integration as the unit was built for classification and verification of the Pocket Rocket thruster and not to be a flight mission. Instead, a mass model was put in place to test that the overall size and fit of boards were satisfactory for the system. The flight mission will use the Intrepid System Board developed in the Cal Poly SLO CubeSat laboratory (PolySat). The System Board has been designed to fit within the CubeSat structure and interface with each subsystem of the satellite [14].

The controller, programmed with a Python script, is controlled via TTY serial over USB with shell commands. Pulse frequencies and durations can be specified in a batch script or they can be commanded on-the-fly for testing purposes. Control comes from a set of GPIO pins on the BeagleBone that are wired to a relay for valve voltage supply.

The DC-RF converter proposed for the integration with the Pocket Rocket system comes from the Stanford University Power Electronics Research Laboratory (SUPERLab), a graduate research lab at Stanford University dedicated to creating innovative, high frequency power converters [15]. The DC-RF converter has been used and tested on other Pocket Rocket Thrusters and has been shown to work [9]. For this project, however, a mass model was put in place and the RF power was supplied from an external power supply fed through a pass-through port into the vacuum chamber. This was chosen to reduce costs, as a new DC-RF converter would need to have been built, and as this particular integration is not a flight model this was deemed unnecessary.

Power delivery for the verification of the Pocket Rocket research is supplied via a SEREN IPS 13.56 MHz sinusoidal signal from a SEREN IPS manual impedance-matched RF amplifier.

CUBESAT INTEGRATION

The Pocket Rocket system is intended for easy integration onto any CubeSat mission. The goal of the project is to come up with a flight ready design of the Pocket Rocket propulsion system that can fit into a 1U CubeSat form factor and be added to any CubeSat mission. The structure is designed to be easily manufactured and assembled into a fully constrained propulsion unit. Figure 6 shows the structure design with all internal components and structural supports for the system. The batteries and gas storage system are constrained by brackets on either end and secured to the bottom of the satellite using a sled that attaches to the side rails. The manifold block then attaches to the rail of the structure to further constrain the assembly. The regulator is attached at the top of the manifold block for easy integration of the piping system. The thrusters themselves are attached to the side panels of the structure. Slots cut out for the screws of the thrusters allow the thrusters to be implemented at any angle to make routing of the gas delivery and RF lines to the thruster easy.

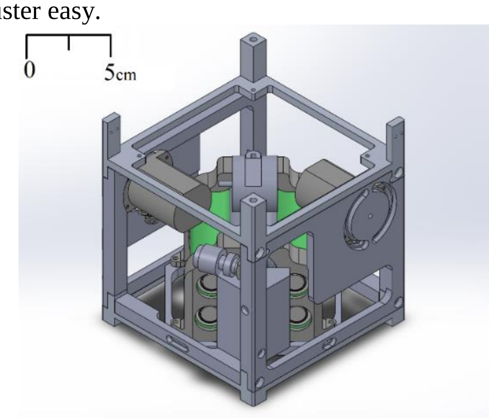

Figure 6: Pocket Rocket CAD model for the proof of concept structure design.

The full structure with all components integrated weighs .9 kg which is less than the limit of 1.33 kg for 1U CubeSats. This proof of concept model made of 6061 aluminum includes two thrusters offset on either side of the satellite to demonstrate and test the individual control over their thrusters as well as the spin induced on the satellite by the thrusters. A fully machined and integrated Pocket Rocket system is shown in Figure 7. The system board mass model is not included in Figure 7, and the BeagleBone controller is significantly larger than an equivalent flight unit valve controller.

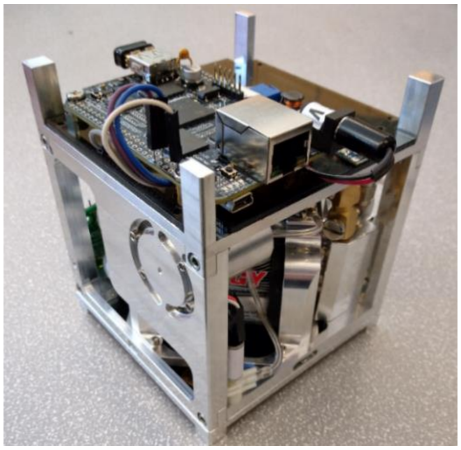

Figure 7: Machined and integrated Pocket Rocket proof of concept structure

RESULTS

The integrated unit was tested in a vacuum environment to replicate space operation. Figure 8 shows two pocket rocket thrusters operating side by side inside the vacuum chamber. Argon plasma (purple in color) can be seen being ejected from the exit of both thrusters. The thrusters, running off the on-board gas storage system at 30 psi have a burn time of over 3 hours. It should be noted, the burn time would significant increase if the current limit of 30 psi on CubeSats was to be removed.

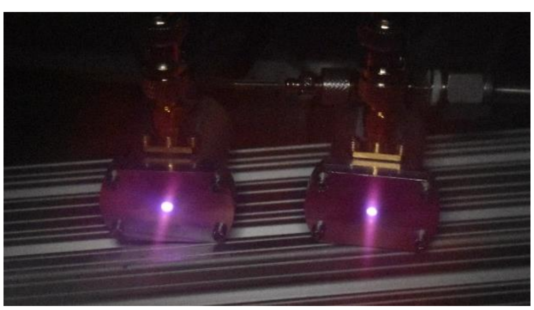

Figure 8: Pocket Rocket thrusters operating side by side in a vacuum chamber test.

Full thruster performance measurements will be made in the near future, once a sensitive thrust balance is constructed at Cal Poly. However, based on operational time and propellant mass stored, expected Δv is around 150 m/s for a 3U CubeSat [16].

Ion Densities in the Plume

To compare key properties of the integrated Pocket Rocket thrusters and ensure that performance is not significantly changed from previous benchtop versions, ion densities were measured in the plume of the thruster using a Langmuir probe. A Langmuir probe works by negatively biasing an electrode to attract the positive ions in the plume. For the measurements of the ion densities inside the Pocket Rocket plume, the Langmuir probe was biased to -45 V. Measuring the voltage drop across a 10 kΩ resistor allowed for the calculation of the current through the probe. Several measurements were taken by holding the plenum pressure constant and varying the power delivered to the thruster as well as by holding the power to the thruster constant and changing the pressures in the plenum. Figure 9 and 10 show the trends of the ion densities in the plume of the thruster at a constant plenum pressure and constant thruster power respectively.

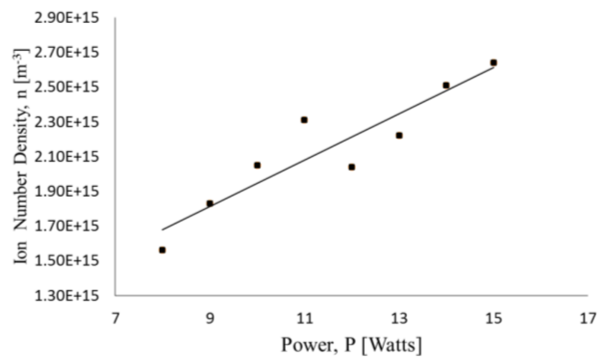

Figure 9: Plot showing the trend in ion density vs power at a constant plenum pressure of 2.6 Torr

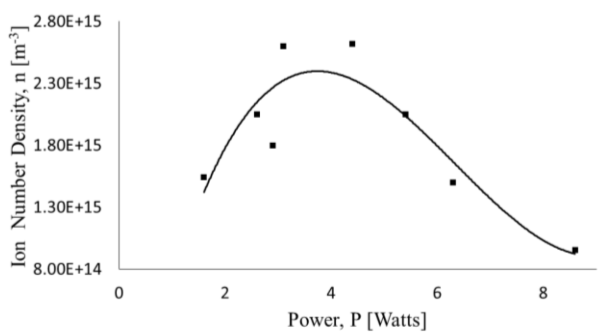

Figure 10: Plot showing the trend in ion density vs plenum pressure at a constant power of 10 W

The Langmuir probe results show that the ion densities in the plume increase linearly with an increased power. Additionally, at a fixed power there is a peak operating pressure that produces the maximum density of ions in the thruster plume. This matches previously noted trends regarding plasma densities inside the discharge tube with power [17] and pressure [6]. Increasing power increases the energy coupled to the neutral gas and therefore results in more ionization and an increase in ion density. The pressure peaks around 4 Torr (plenum pressure), corresponding to the minimum of the Paschen breakdown curve. The absolute values of ion densities in the plume are approximately two order of magnitude lower than in the center of the discharge tube [6,17]. However, this is expected as ion and electrons neutralize as they move away from the RF coupling at the center of the discharge tube. Computational Fluid Dynamics (CFD) simulations of the Pocket Rocket thruster indicate a two order of magnitude decrease from the center of the tube to the plume [18]. These results show that the integration process has not impeded operation of the thruster.

Electrothermal plasma thrusters are reasonably efficient and provide reliable control on spacecraft with low mass. This makes the Pocket Rocket design a potential thruster for use on CubeSat missions. The collisional heating within the Pocket Rocket discharge tube results in volumetric expansion exhausting the heated gas into space at increased velocities over cold gas. The thermal velocity (v_{th}) of the exhausted gases are related to the gas temperature by Equation 1,

$$v_{th}=\sqrt{\frac{8kT_g}{\pi M}} \quad (1)$$

where k is the Boltzmann constant, and T_g and M are the gas temperature and particle mass, respectively. The corresponding thrust (T) approximated for a heated gas exhaust is given by Equation 2,

$$T=\dot{m}v_{th} \quad (2)$$

where $\dot{m}$ is the propellant mass flow rate. The gas temperature and thrust are positively correlated. Heating of the propellant gas in Pocket Rocket occurs through ion neutral charge exchange collisions and wall heating from ion bombardment [8]. Therefore, the higher the number of ions in the discharge, the higher the expected gas temperatures. Based on the Langmuir probe density measurements, the integrated Pocket Rocket thrusters should produce the highest thrust and specific impulse at plenum pressures of 4 Torr.

CONCLUSION

As the CubeSat industry continues to expand, mitigation of low Earth orbit crowding and desire for deeper space exploration drive the need for propulsion systems on CubeSats. Pocket Rocket, a light weight, inexpensive, scalable, and efficient micro plasma thruster is one solution for on-board propulsion. Research done at California Polytechnic State University, San Luis Obispo has constructed a compact, viable design that integrates the entire propulsion system including a gas delivery and storage system, a power storage and control system, and two independent thrusters into a 1U CubeSat form factor. With the on-board pressure regulation of 30 psi the thruster burns for over 3 hours. For power usage of less than 10 W supplied at 13.56 MHz the thruster is expected to provide on the order of 1 mN of thrust.

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