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Monopropellant Micropropulsion System for CubeSats

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ABSTRACT

Stellar Exploration Inc. has developed a high performance Hydrazine Monopropellant Micro Propulsion system for use with CubeSats with focus on manufacturability and affordability. The 1kg micropropulsion system will be coupled to one or two additional 1kg CubeSat units making an overall 2-3kg two or three unit CubeSat system compatible with California Polytechnic State University's P-POD deployment system. The micro propulsion system includes four 1.5 Newton thrusters arranged appropriately to control roll, pitch, yaw and axial translation. The monopropellant micropropulsion system required many innovations in order to miniaturize it to meet the geometric and mass requirements of CubeSats. These innovations include the use of specially designed catalysts, micro solenoid thruster valves and micro machined combustion chamber and nozzle. This paper outlines the decision processes involved in choosing the type and configuration of the micro prolusion system as well as a detailed description of the innovations leading to a functional system. Future improvements and lessons learned from development will also be discussed and concluded with the micro propulsion test results.

Introduction

The design philosophy used throughout this project includes simplification, the use of commercial of the shelf components, and rapid prototyping to support component and system testing. The use of as many commercial-off-the-shelf components as possible is very important for developing a system like this rapidly. Commercial-off-the-shelf components can provide a starting point for a design and allow for a big picture of the system to be developed early on. Significant cost savings are another result of using commercial-off-the-shelf components when available as opposed to a custom part. These components along with keeping the system as simple as possible at the beginning design stages helps insure project success.

The CubeSat standard which outlines requirements for proper function inside the Poly Picosatillite Orbital Deployer (P-POD) was followed during design and development.

Propulsion System Development

Many trade studies were conducted during the development of the Micropropulsion system. Some initial trade studies included propellant type, number and arrangement of thrusters, and blow-down vs. pump fed systems. The main factor driving the decisions in the initial trade studies was simplicity. From this the blow-down system was chosen over the pump fed system and Hydrazine was chosen for the propellant because of the long heritage of its use. The thruster arrangement consists of 4 thrusters mounted to the rear face of the Micropropulsion system canted 5˚ outward. This is the simplest arrangement while controlling roll, pitch, yaw, and axial translation.

The performance goal for the propulsion system based mission analysis for a significant orbit change is a ΔV = 500m/s. From this initial performance specification the required dry mass fraction may be plotted against specific impulse in order to estimate the allowable dry mass of the system and is shown in the figure below. Most commercial monopropellant thrusters achieve specific impulses between 210-230sec. In this range a maximum dry mass fraction of 80-82% is allowable for a ΔV = 500m/s. This assumes a 3 unit CubeSat with a wet mass of 3kg. From this a maximum dry mass fraction for the Micropropulsion unit of 0.4-0.46kg was calculated.

To estimate proper thrust requirements, the thrust to weight ratio of past spacecraft with similar mission objectives was studied. This process was described in "Space Propulsion Analysis and Design". A general trend in past spacecraft includes a thrust to weight ratio of at least 0.2 for missions requiring orbital transfer. A thrust to weight ratio of 0.25-0.35 will be considered. The mass of the 3-unit CubeSat is defined as 3 kg, following the past trends of spacecraft, a total thrust level of around 7.4-10.3 Newtons is recommended.

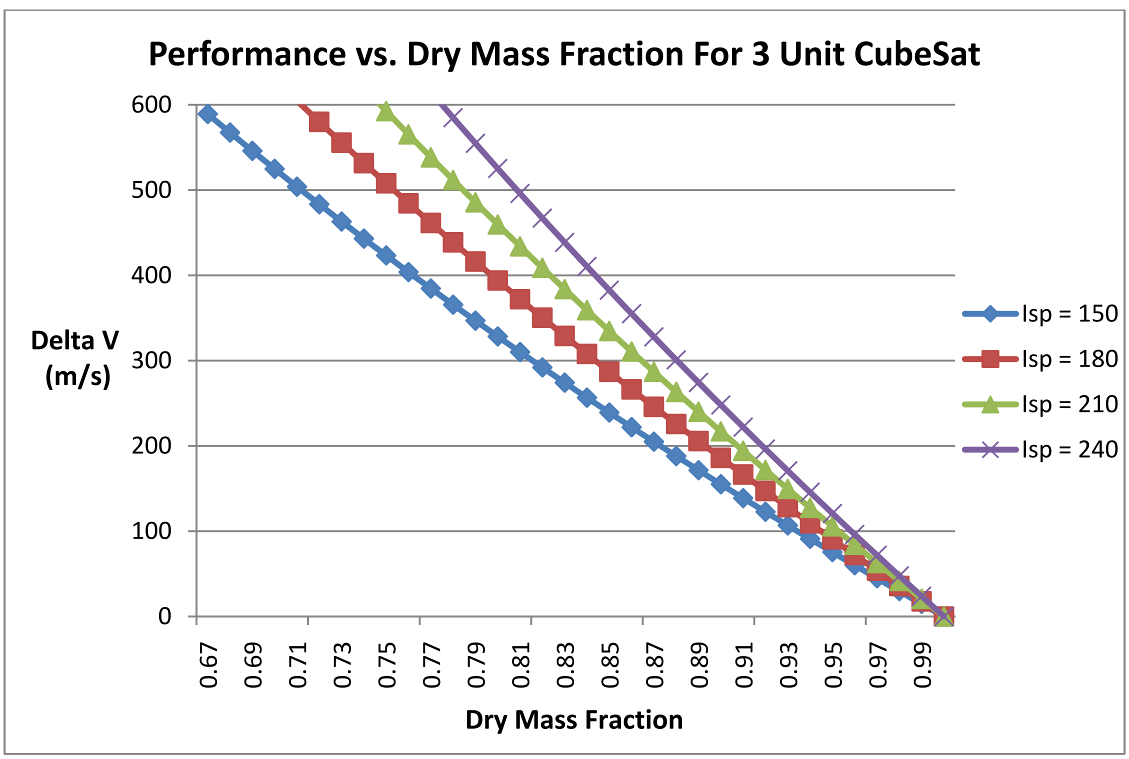

Figure 1. Performance vs. Dry Mass Fraction for various I_{sp} values.

For this project, the thrusters will be designed to fall near these values and adjusted if empirical testing deems necessary. This requirement puts more importance on valve response and the control system to act quickly to pulse the thrusters for orbital maintenance and attitude control since the thrusters may be oversized for these types of maneuvers. This is necessary to ensure proper thruster performance for orbital transfer capability.

The desired mass flow rate of propellant can be calculated using the desired thrust and expected or assumed specific impulse. A thrust of 1.5N per thruster and a specific impulse of 220sec was assumed which leads to a mass flow rate of 0.7g/sec per thruster. From the desired mass flow rate and assumed chamber pressure and using gas dynamics the appropriate throat diameter can be calculated which for this case is approximately 2mm. This assumes a combustion chamber pressure of 550kPa. The combustion chamber dimensions were derived using some historic length over diameter ratios with the diameter calculated using gas dynamics and an assumed combustion chamber inlet velocity of Ma =0.1.

In order to specify the nozzle expansion ratio, a study was conducted evaluating the overall theoretical performance as the expansion ratio is increased. However, as the nozzle expansion ratio increases the overall height of the tank must decrease which also decreases the volume of propellant contained. Shown in the figure is the theoretical specific impulse vs. nozzle area expansion ratio. From this an expansion ratio of 15 was chosen since it gives the best overall performance.

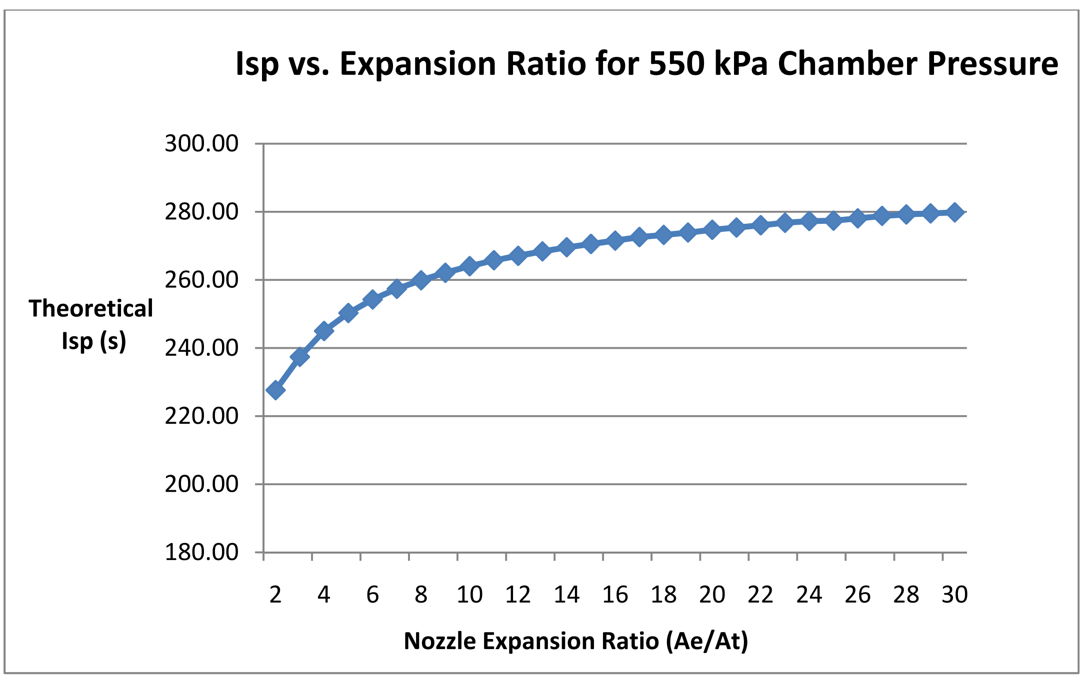

Figure 2. Plot of theoretical I_{sp} vs. Nozzle Expansion Ratio for a chamber pressure of 550 kPa.

The initial tank pressure will be 1100kPa. This is based on an assumed minimum operating pressure of 220kPa and a blow down ratio of 5. From the initial tank pressure and required mass flow rate, the thruster valve can be specified. An off the shelf micro solenoid valve from ASCO was chosen to begin testing with.

The catalyst designed for this application is a disc consisting of a platinum/iridium wire ring with platinum wire mesh laser welded to it. These discs are then stacked and held together with a stainless steel stud. The prototype of the catalyst is shown in Figure 3.

Propulsion system Concepts

A propulsion system tank and cap structure with the CubeSat interface and rails for the P-POD integration, using 7075-T6 Aluminum and CNC machining was the proper solution considering the time, size, and cost constraints. Aluminum 7075-T6 was chosen for the propulsion system tank and cap because of its superior mechanical properties compared to 6061-T6 and its accepted use per the CubeSat standard. Three prototype assemblies were designed and their theoretical performance calculated. These prototypes consist of both a cubic tank and cap design which maximizes propellant volume and two cylindrical tank and cap designs which minimize mass. These designs have wall thicknesses and geometries in order to contain pressures up to 1100kPa without yielding or leaking.

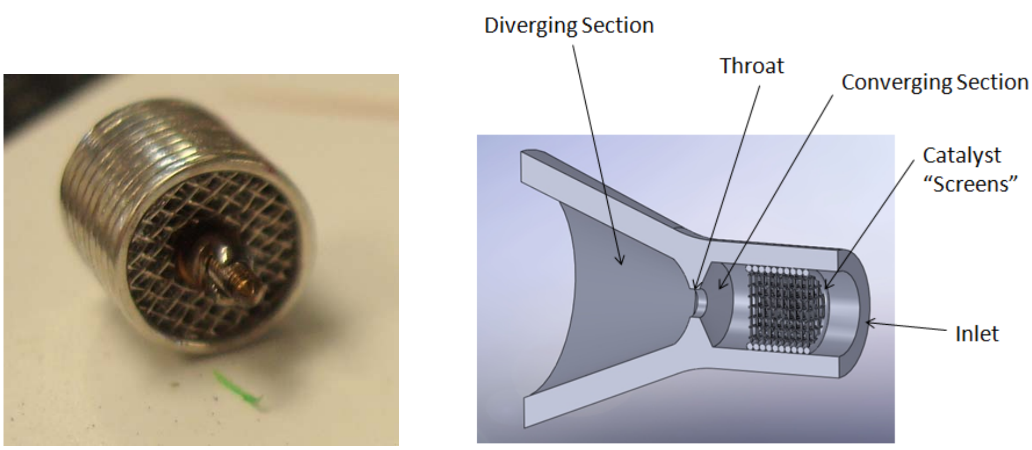

Figure 3. Prototype catalyst (left) with nozzle and chamber section view (right).

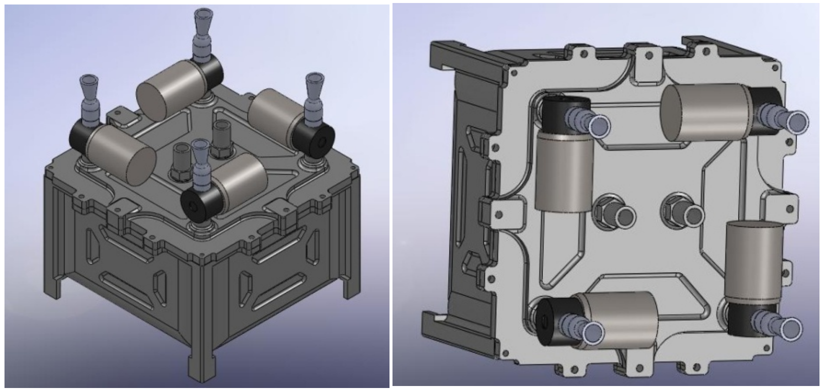

Figure 4. Cubic tank and cap prototype micropropulsion system assembly.

The design shown above has a large internal volume capacity, but due to the large internal radii at the corners in order to reduce stress concentrations has a larger mass than a cylindrical tank. As per the CubeSat standard the mounting flanges of the tank and cap protrudes 6mm from the four faces to allow access to the fasteners. This still allows for a 0.5 mm clearance with the P-POD walls while loaded in the P-POD. This design, while slightly less mass efficient, easily incorporates guide rails and utilizes the extra mass contained in the four vertical corners to satisfy the rail requirements as stated in the CubeSat standard.

A cylindrical tank was designed in order to reduce the dry mass required by the cubic tank while attempting to achieve internal volume capacity at or near that of the cubic tank design. Shown in Figure 5 is the cylindrical tank assembly with integrated guide rails as required by the CubeSat Standard.

The cylindrical tank shown below reduces the overall mass of the assembly but at the expense of a large amount of fuel. As can be seen in Figure 5, a large amount of volume is wasted in the open space in the corners. While the wall thickness for this design is drastically reduced when compared to the wall thickness required for the cubic tank, too much propellant volume is lost.

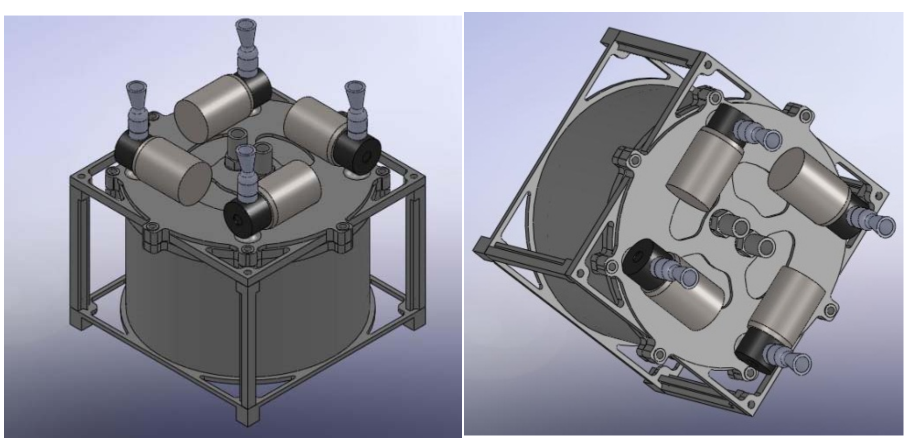

Figure 5. Cylindrical tank and cap prototype micropropulsion system assembly.

Because of the overall length of the thruster assembly, the cubic and cylindrical tanks shown in Figure 4 and 5 are shorter than expected in order to meet the required maximum length. A second iteration of the cylindrical tank design includes a longer, narrower tank in order to mount the valves along the axis of the tank at the four corners of the assembly allowing for more tank height (Figure 6). This prototype was created in order to investigate if more internal volume can be gained while still achieving the lower mass benefits of having a cylindrical tank design.

A table was created listing propulsion assembly dry mass and internal volume, along with an estimated overall spacecraft performance to compare the three concepts (Table 1).

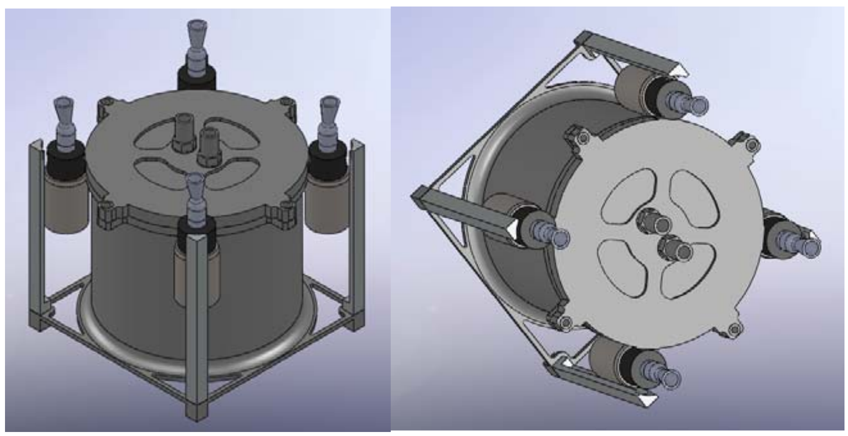

Figure 6. Cylindrical tank with vertically mounted thruster prototype Micropropulsion system assembly.

Table1. Tank geometry, mass, volume and corresponding delta V.

Tank Shape and Description	Tank Dimensions (mm)	Volume Capacity (ml)	Assembly Mass (g)	Propellant Mass (g)	Fueled System Mass (kg)	Dry Mass Fraction (%)	Delta V* (m/s)
Cubic Tank and Cap with thruster mounted to cap	100 X 100 X 55	475.00	433.00	522.50	955.50	0.45	419.86
Cylindrical Tank and Cap with thrusters mounted horizontally	97 O.D. X 77.85	443.00	345.00	487.30	832.30	0.41	407.48
Cylindrical Tank and Cap with thrusters mounted vertically	89 O.D. X 80	457.00	369.00	502.70	871.70	0.42	415.32

*Assumes 220 second Isp

As shown from Table 1, the theoretical performance of the cubic tank is the largest of the three designs even though it has the highest unit dry mass fraction. The reason for this is because the cubic tank can hold much more propellant mass than the other two and when evaluated as a 3-unit CubeSat configuration the extra mass of propellant is of more importance than the greater mass of the tank. The cubic tank design is also beneficial from a manufacturability standpoint. The cubic tank shape is more easily manufactured with a CNC mill than the cylindrical tanks because of the undercuts required for the mounting flanges.

Test Results

After valve function and o-ring seal tests were conducted a system burst test was carried out. Using nitrogen gas as a pressurant source, the internal pressure of the Micropropulsion system was increased slowly until failure. This occurred at 2310kPa, 2206kPa, and 2027kPa resulting in factors of safety of 1.9, 1.8, 1.7 respectively. Observed was a leak before burst failure mechanism which is desirable because of the catastrophic failure of tank bursts. The main sealing o-ring was pushed out of the groove between the tank and cap allowing the gas to escape during failure as shown below in Figure 7.

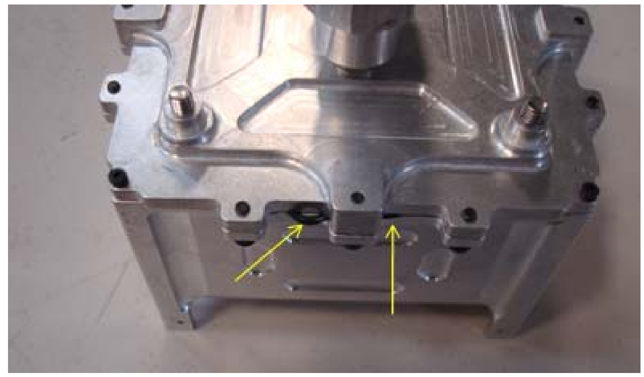

Figure 7. O-ring shown protruding out of the tank and cap**.**

A hot-fire test was conducted with 50g of anhydrous hydrazine at a starting pressure of 690kPa. One thruster was operated at 0.25 and 0.5s pulse widths. Incomplete decomposition was observed. Both ammonia vapor and hydrazine liquid droplets were exhausted through the nozzle.

Figure 8. Propulsion system fueling (left) and test stand (right).

Future Work

A second hot-fire test will be conducted with a modified catalyst and nozzle throat. The catalyst assembly will be increased in length by 40% and tested with the current nozzle. Following that, a second nozzle will be tested with a 20% smaller nozzle diameter. Based on the results of these tests more modifications to the catalyst and nozzle will be made as needed.

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