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Performance Testing of a CubeSat-scale Electrolysis Propulsion System

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Electrolysis propulsion systems are well-suited for the CubeSat scale because of their simplicity, flexibility in the use of electrical power, and dense propellant storage. Such a system provides an estimated 1 km/s of ΔV, which would be a significant improvement in the capabilities of CubeSats, offering the prospect of interplanetary missions. The propulsive performance of these systems has not yet been well-characterized, preventing their use in flight-demonstration missions. A prototype system, as well as a method for testing the performance of electrolysis propulsion are presented, with the aim of advancing the technology sufficiently for an on-orbit demonstration.

I. Introduction

CUBESATS have become popular tools for scientific research in low earth orbit (LEO) in the past decade. Advances in other areas of satellite development have made it possible to conceive of missions involving CubeSats outside of LEO.[1,2] Propulsion systems designed specifically to provide high ΔV at a CubeSat scale have been identified as a necessity for CubeSat missions beyond LEO.[3] Some of the mission concepts to date involve launching propulsionless CubeSats as secondary payloads on launch vehicles already on interplanetary trajectories, or launching a host of CubeSats on a single, interplanetary primary spacecraft.[4] Not only do these concepts of operations limit the potential targets of exploration –and therefore the potential science goals—but it also means that the satellites will have no useful control over their orbits once deployed.

CubeSats capable of orbit control can perform a different range of scientific missions from fixed-orbit satellites and can even replicate some of the capabilities of larger spacecraft on a much smaller budget. However, miniaturization of large-scale systems down to a CubeSat scale, especially those propulsion systems involving gaseous propellant, cryogenics, multiple propellant tanks or high power consumption, can lead to low ΔV designs due to the unfavorable scaling of these systems. Propulsion concepts derived from larger spacecraft and adapted to fit in a 3U envelope have several disadvantages. One is that propellant tanks for gaseous propellants do not scale down well; so, a larger fraction of the propulsion system’s mass will be taken up by the tank structure. However, in order to carry a significant amount of gaseous propellant in a CubeSat-sized spacecraft, the propellant must be stored at high pressures. Pressurized tanks conflict with the CubeSat spec, which calls for low pressure tanks (1.2 atm) with factors of safety of four or higher.[5] Another disadvantage is that the electrical power requirements the propulsion system might not scale with the size of the system. For some missions, the power consumption of the propulsion system might require the use of deployable solar panels or abundant energy storage. Even when CubeSats can use deployable solar panels to provide enough power for electric propulsion systems, doing so likely comes at the expense of the payload or other bus subsystems. The likely solution, precluding other subsystem functions during propulsion operations, significantly limits mission architectures.

A propulsion system that exploits the benefits of the CubeSat scale and that can provide a significant amount of ΔV would be advantageous for CubeSat missions beyond low earth orbit and can change the way CubeSats are viewed and used by the science and technology communities. This paper presents efforts towards validation and performace testing of an electrolysis propulsion system designed this scale. Using the advantageous parts of both electric and chemical propulsion, electrolysis propulsion systems take energy from solar panels and stored liquid water to generate a gaseous bipropellant mixture. In doing so, such systems preclude the need for batteries to store power meant for propulsion; the energy is stored in the propellant, as is the case for chemical systems, but without

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pressurization, cryogenics, or the need to handle and launch combustible materials. Similar propulsion concepts have been proposed for much larger spacecraft.[6,7,8] While the system described in this paper uses the same principles of operation, it is far less complex in its operation and is designed specifically to take advantage of the small scale of CubeSats. So far, only low ΔV propulsion systems for CubeSats have been flown in space.[9,10] The type of electrolysis propulsion system described in this paper is well-poised to provide CubeSats with versatile, high ΔV propulsion.

II. Operation of an Electrolysis Propulsion System

A. System Description

Research into electrolysis propulsion systems at Cornell University has led to a prototype that consists of three major components. The water tank is where the liquid water propellant is stored, and also contains the electrolyzers that break the liquid water into its component gases. Each burst of gaseous propellant is ignited inside the combustion chamber. Lastly, the gases are expanded through a nozzle, generating thrust.

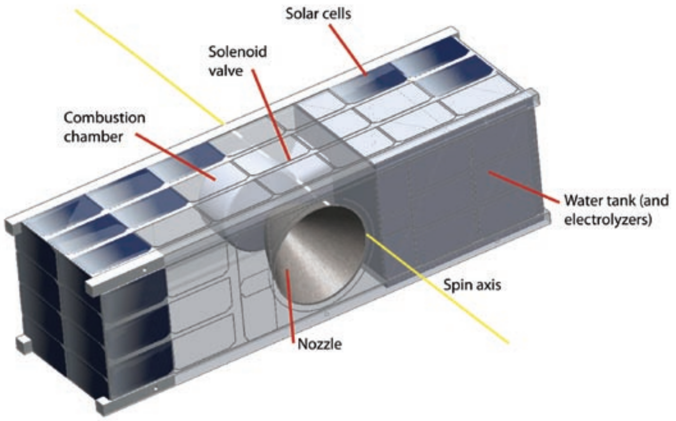

Figure 1. Layout of an electrolysis propulsion system within a 3U satellite bus. *The propulsion system occupies 2U of the 3U volume with a 1L liquid water tank.*

A candidate arrangement of these components inside a 3U satellite bus is shown in Figure 1. The satellite spins about an axis through the center of gravity (CG) and normal to the face that includes the thruster, as shown in Figure 1. The system is meant to occupy most of 2U, leaving at least one U in a 3U satellite free for payload and other components. The propellant tank is placed in the outboardmost section of the spacecraft, and is connected to the combustion chamber via an actuated solenoid valve. The combustion chamber's axis of symmetry is aligned with the thrust axis. The nozzle is centered in the bus structure, directly in front of the combustion chamber. As the propellant is consumed, the center of gravity of the satellite shifts away from the side with the propellant tank, displacing the spacecraft's spin axis. The nozzle's axis of symmetry is placed midway between the spin axis at the start of the mission and the spin axis at the end of the mission to minimize the overturning torque due to thrust pulses, as discussed below.

Figure 2 shows a schematic of the energy and propellant flow between the different components of the propulsion system. Energy for the operation of the electrolysis propulsion system comes from solar panels. Several concepts for deployable solar arrays for CubeSats exist, which provide power on the order of 30 W to 50 W.[11] However, because electrolysis propulsion systems are flexible in their power consumption, this paper considers only the use of body-mounted solar panels. Electrical power from the solar panels is used to power several electrolyzers. The specific heat of formation of water is -15.87 kJ/g, meaning that it takes 15.87 kJ to electrolyze a gram of water into its component gases. This required energy can be supplied quickly, drawing as much available power from the solar panels as possible, or slowly, leaving plenty of power

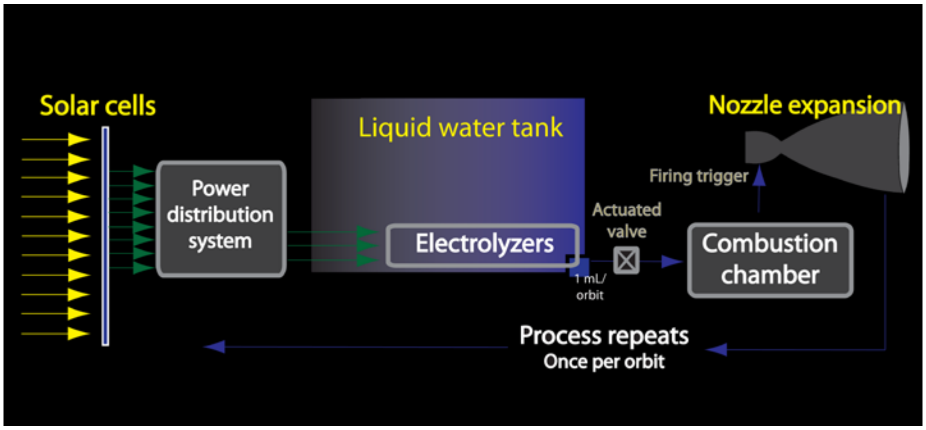

Figure 2. Schematic of the operation of a CubeSat electrolysis propulsion system. *Solar cells power the propulsion system, which operates by combusting hydrogen and oxygen gas electrolyzed from liquid water.*

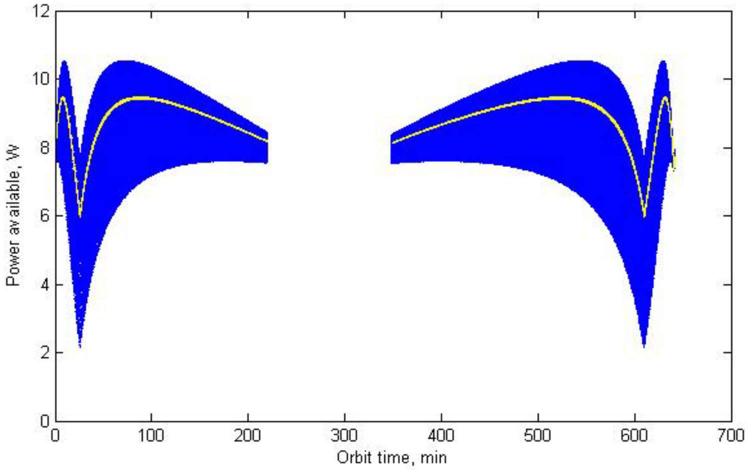

Figure 3. Electrical power available to a CubeSat in an example GTO orbit. *The blue line shows the power for a rotating 3U CubeSat using body-mounted solar panels. The yellow line shows the power averaged to remove the effects of spacecraft rotation.*

for communications equipment, payload and other subsystems. The energy is effectively stored in the chemical potential energy of the electrolyzed gases. This flexibility in the rate of electrolysis allows for a tradeoff between the power used for electrolysis and the time taken to electrolyze the water. This tradeoff means that electrolysis propulsion systems, unlike many electric thrusters, only require high power if the mission does not allow for extended periods of time between thruster firings. Using 7.3 W, 3U solar panels and 2.1 W, 1U panels from ClydeSpace[11] as an example of the characteristic power available using body mounted panels, it is possible to calculate the power available in an example orbit. Figure 3 shows the power available in a GTO orbit for a spacecraft with body-mounted panels rotating at the rate of 2 rad/s. This orbit is assumed to be the initial orbit for a GTO-to-lunar-orbit transfer. GTO is also the point in this mission where the least energy is available per orbit—the worst case—since the time spent in the shadow of the Earth is longest and the orbit period is shorter than for higher orbits.

The electrolyzers inside the water tank of this prototype are commercially-available proton exchange membrane (PEM) electrolyzers. The platinum electrodes in these electrolyzers are separated by a proton exchange membrane that allows protons to cross and complete the circuit. PEM electrolyzers do not require dissolved electrolytes in the water; so, distilled water is used as propellant in the propulsion system. The efficiency of this model of PEM electrolyzer in converting electrical energy into chemical potential energy of the electrolyzed gases has been measured to be in the 85% - 90% range.[12]

The electrolyzers are powered only during the sunlit portion of the orbit. Electrolysis increases the pressure of the water tank as the amount of gas increases. Once the hydrogen and oxygen mixture reaches a high enough pressure (currently set for 10 bar) a solenoid valve opens between the propellant tank and the combustion chamber. This event supplies the combustion chamber with a mix of hydrogen and oxygen ready to ignite. A small spark plug driven by a capacitive ignition circuit causes the gas mixture to combust. The gas then expands through a convergent-divergent nozzle, which produces the thrust necessary to impart a ΔV on the satellite. Each pulse is expected to last approximately 0.45 seconds.

B. System Operation in a 3U Satellite

The thruster operates in a pulsed mode, with each pulse occurring after the electrolyzed gas reaches its required pressure. Each burst of the thruster consumes about 1 g of propellant, meaning that a 1 L propellant tank can provide roughly 1000 pulses. The ΔV provided by each pulse varies throughout the lifetime of the mission as the mass of the spacecraft decreases. Figure 4 shows the ΔV per burst for an example mission, which starts from a GTO orbit and fires the propulsion system at the perigee of every orbit to raise the apogee. The average ΔV per burst for this mission is 1.9 m/s, based on an estimated 350s for specific impulse.

The thruster relies on the successful separation of electrolyzed gases from the

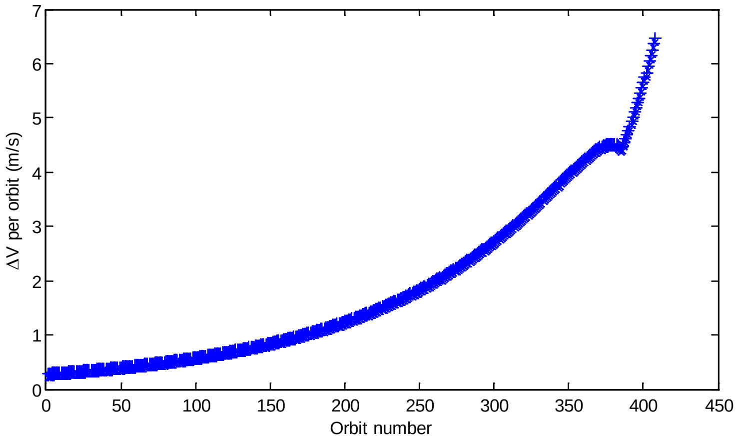

Figure 4. ΔV per burst for a typical mission. *Initial orbit is a geosynchronous transfer orbit.*

liquid water. To accomplish this propellant management, the spacecraft is in a constant spin about its major axis of inertia. This spin provides several advantages to the spacecraft. The centrifugal force caused by the spin separates the gas and liquid, causing the gas to accumulate toward the inboard side of the satellite, while the water is pushed to the outside edge of the water tank. A diagram of this separation is shown in Figure 5. A spin set up by magnetic torquers at the beginning of the mission would also provide passive robustness to misalignments in the thruster and torques due to firing despite having a shifted center of gravity. For typical payload configurations, the center of gravity will shift by an estimated 0.032 m during the lifetime of the mission, for the example of a uniformly dense 1U payload section. This shift takes place throughout the mission because the propellant tank is located on one side of the satellite and as the propellant is consumed, the satellite's mass distribution will change. While the shift in CG is small, judicious timing of engine firings or simply a fast-enough rotation of the satellite can mitigate the nutation caused by a torque about the center of mass on a spinning satellite.

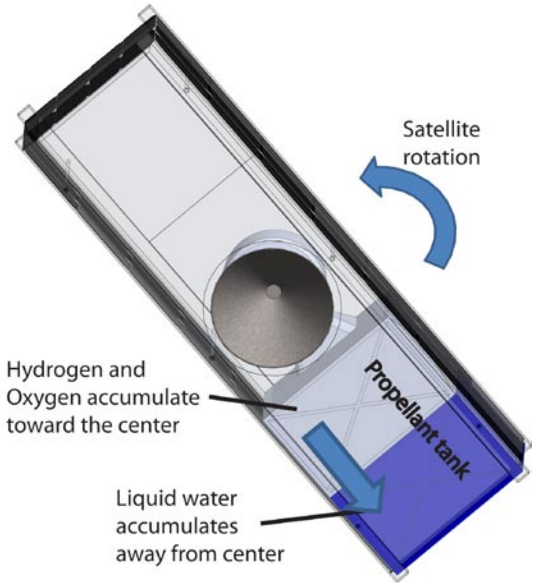

Figure 5. Diagram of CubeSat rotation. *Rotation primarily helps in the separation of electrolyzed gases.*

III. Performance Metrics for CubeSat Propulsion Systems

Metrics to evaluate the performance of CubeSat propulsion systems currently do not capture all of the evaluation criteria necessary at this scale. Many of the metrics seen in the CubeSat literature today are derived from rocketry applications for larger spacecraft such as specific impulse and total ΔV.[3] These are still very much relevant for CubeSats and similarly-scaled spacecraft but do not completely capture the nuances of propulsion systems at such small scales. It is therefore useful to enumerate the characteristics of a successful propulsion system at a CubeSat scale:

1. High specific impulse
2. High ΔV
3. Low toxicity of the propellant
4. Low maximum pressure of the system at launch
5. Complete compliance with the CubeSat standards
6. Small volume used for the propulsion system and related hardware
7. Low electrical power

Ranking propulsion systems developed for use in CubeSats according to these desired characteristics would yield a comparison between systems that takes into account the envelope in which the propulsion system is used. There is no general metric or combination of metrics that would allow a universally objective ranking in all situations, but rather a thorough evaluation of the criteria above in the framework of the mission at hand does yield a more informed perspective on the design and choice of a propulsion system. For example, not all missions require that the propulsion system be low power. If a satellite is already carrying deployable solar panels, which are primarily meant to be used to power an experiment after the satellite is already in its final orbit, then power concerns during the propulsive phase may not be limiting. In the more general case where the propulsion system provides the largest constraints on the satellite's power subsystem, then a desirable system uses little power and also allows for flexibility in the scheduling of electrical power.

IV. Performance and Validation Tests for Electrolysis Propulsion Systems

A. Prototype Electrolysis Propulsion System for Ground-Based Tests

Successful characterization of the specific impulse and ΔV capabilities of an electrolysis propulsion system requires the testing of a prototype brassboard system in a relevant laboratory environment. The prototype system developed at Cornell University's Space Systems Design Studio has the same inner dimensions that a flight version

Figure 6. PEM Electrolyzer mounted inside water storage tank.

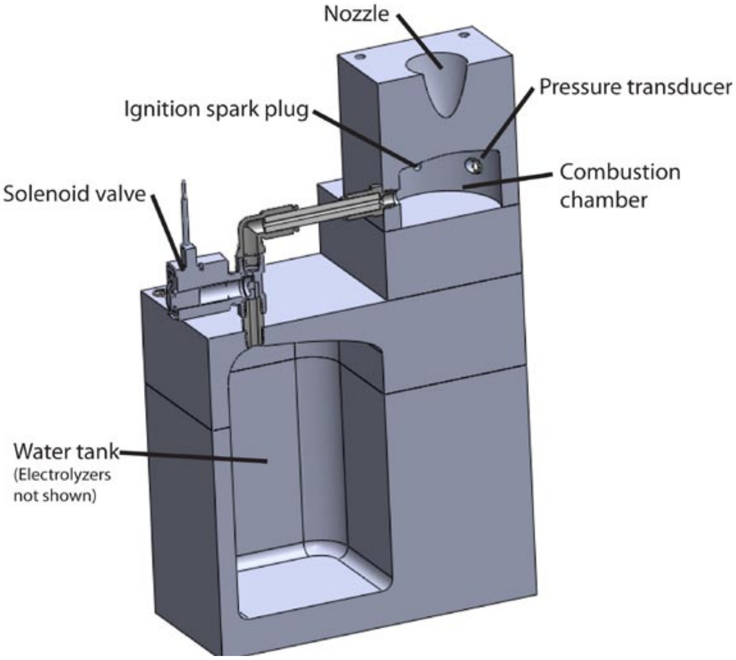

Figure 7. Cutaway of prototype electrolysis propulsion system. *The system is analogous to a flight version, but designed for tests in a vacuum chamber.*

would have, and it is designed for testing in a vacuum environment. Testing in earth's gravity simplifies the operation of the thruster because there is no need to spin the propulsion system to provide the acceleration field that achieves gas separation.

The components of the brassboard prototype are analogous to the components of the flight version described above. A single tank stores the liquid water propellant and electrolyzed gases. Three electrolyzers are installed inside the tank. One of these is shown in Figure 6 mounted in the propellant tank. Electrical power is supplied to the electrolyzers from an external power supply, through an electrical feedthrough installed in the tank. A pressure transducer mounted on the tank monitors the internal pressure of the tank to indicate when the pressure is high enough for a firing to occur.

Gas is allowed to flow into the evacuated combustion chamber when the pressure is sufficiently high, above 10 bar for the test prototype. A solenoid valve controls the flow of gas into the combustion chamber. A miniature spark plug ignites the hydrogen and oxygen mixture inside the combustion chamber moments after the gas is initially allowed to flow into the combustion chamber. A microcontroller sets the timing between the opening of the valve and the firing of the spark plug. This delay is optimized to produce the maximum ΔV per firing. The nozzle has the same internal dimensions as a flight nozzle but is built into a solid block of aluminum for simplicity and in order to provide a more rigid attachment with the combustion chamber and main tank assembly. Figure 7 shows a cutaway view of the prototype propulsion system, with the main components and sensors labeled.

The entire assembly is oriented such that the nozzle's axis of symmetry is perpendicular to the ground and so that firing causes a downward force. Force measurements are taken by four strain gauges mounted on a plate upon which the prototype assembly is set. Both force and the change in mass of the prototype are measured, to give a clear picture of both the thrust profile and total ΔV per burst. Force measurements are taken at millisecond intervals and the data is recorded through a data acquisition card outside of the thermal vacuum chamber. Pressure inside the combustion chamber is also monitored through a pressure transducer. Figure 8 shows the prototype and force measurement setup inside the thermal vacuum chamber.

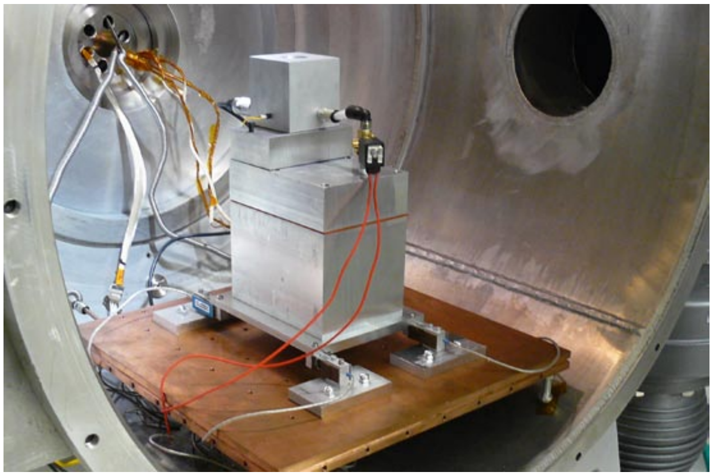

Figure 8. Prototype electrolysis propulsion system on thrust measurement assembly in Cornell's thermal vacuum chamber.

V. Conclusion

Electrolysis propulsion systems such as the one described in this paper hold great promise for future implementation in CubeSats. Their concept of operation takes advantage of the small scale and restricted envelope of the CubeSat, providing a propulsion system that fits in naturally at the CubeSat scale and provides enough ΔV to be of use in low earth orbit as well as interplanetary missions. In small satellilte and CubeSat missions, where all of the spacecraft subsystems are closely integrated, the utility of propulsion systems must be evalulated on a mission-specific basis, and not simply using traditional propulsion metrics. Concerns such as power use, the toxicity of propellants, the tank pressures at launch and compliance with other CubeSat standards have a significant impact on the utility of propulsion systems for these types of missions and should be taken into account when comparing propulsion systems at this scale.

Specific impulse, total ΔV and impulse-bit are still very useful figures for propulsion systems, especially once a selection has been made. It is important to test a propulsion system in an environment as similar as possible to the one in which it will operate, in order to solve any potential problems and accurately measure its performace. The electrolysis propulsion system developed at Cornell University will be tested in a thermal vacuum chamber, where the specific impulse and ΔV per burst will be measured. Results from these ongoing tests will be posted on the group's website, www.spacecraftresearch.com. These tests aim to further validate the system and increase its technology readiness level, opening the possibility of development of a flight version for a CubeSat demonstration mission. A CubeSat mission demonstrating the high-ΔV capabilities of this propulsion system would greatly increase the viability of future CubeSat missions far beyond low earth orbit.

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