Photovoltaic Electrolysis Propulsion System for Interplanetary CubeSats

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Abstract— **CubeSats are a new and emerging low-cost, rapid development platform for space exploration research. Currently, CubeSats have been flown only in Low Earth Orbit (LEO). Advancements in propulsion can enable these spacecraft to achieve capture orbits around the Moon, Mars and beyond. Such enabling technology can make science-focused planetary CubeSat missions possible for low cost. However, Cubesats, because of their low mass, volume and launch constraints, are severely limited by propulsion. Here we present an innovative concept that utilizes water as the propellant for a 6U, 12 kg, Interplanetary CubeSat. The water is electrolyzed into hydrogen and oxygen on demand using onboard photovoltaic panels, which would, in turn, be combusted to produce thrust. However, important challenges exist with this technology including how to design and operate high efficiency Polymer Electrolyte Membrane electrolyzers at cold temperatures, how to efficiently separate the water from the hydrogen and oxygen produced in a microgravity environment and how to utilize the thrust generated to produce efficient trajectories. Our proposed solution utilizes a centrifuge that separates water from the reactants. The system uses salts, such as lithium chloride, to reduce the freezing point of water. Our techniques identify a method to operate the propulsion system up to -80 ^{o}C. Analysis of the combustion and flow through the nozzle using both theoretical equations and finite-volume CFD modeling shows that the specific impulse of the system is in the 360 s to 420 s range. At this efficiency, and from preliminary results a 12 kg CubeSat with 7.8 kg of propellant provides a ΔV of 4,400 m/s. In theory, this is sufficient for Lunar or Mars capture orbits once deployed from LEO. These feasibility studies point to a promising pathway to further test the proposed concept.**

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1. INTRODUCTION

CubeSats offer a low-cost approach to exploration of space and are at present confined to LEO. CubeSat have become possible thanks to the miniaturization of computer electronics, sensors, and electro-mechanical systems (particularly attitude control and determination systems) and the proliferation of low-cost, high-efficiency solar photovoltaics. However, propulsion systems have not caught up. The small volume and mass of CubeSats, together with safety concerns, have restricted the use of propulsion systems on CubeSats. A few CubeSats are being designed to be dropped off by a mothership on Earth escape trajectories intended for Lunar and Martian flyby missions (see Figure 1). Advances in propulsion can enable CubSats to achieve capture orbits around the Moon, Mars and beyond.

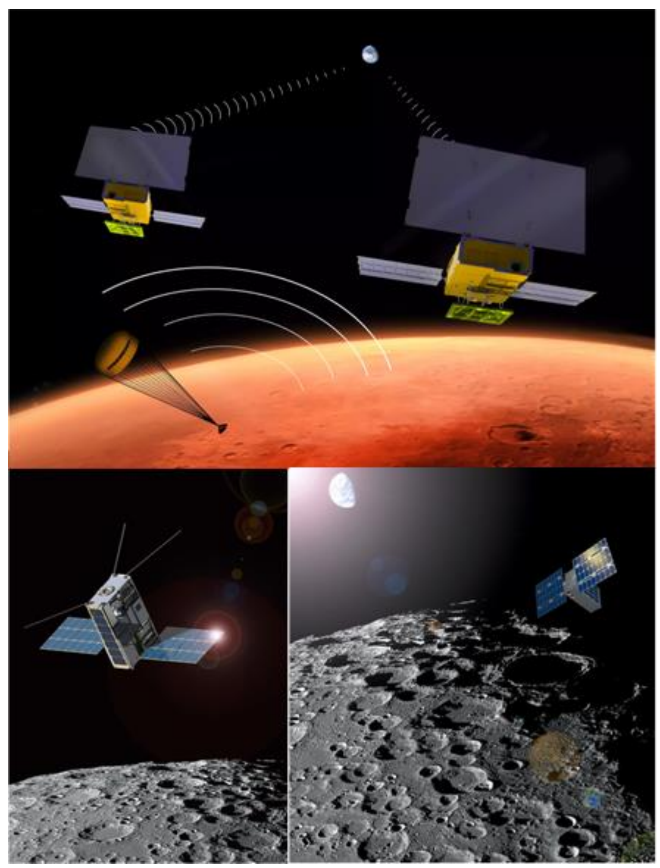

Figure 1. Interplanetary CubeSat missions including (Top) MARCo CubeSats that will relay information from Mars Insight [1]. (Bottom Left) Lunar IceCube will map the lunar South Pole use thermal spectrometer [2]. (Bottom Right) LunaH-Map will map the lunar South Pole using a neutron spectrometer [3].

Current CubeSats have used propulsion systems for orbit raising maneuvers and attitude control. These include cold gas systems that are well understood and store an inert gas or refrigerant. They have low specific impulse of 100 s or less, but can offer high thrust. Alternatives include electrical propulsion systems such as resistojets, electrospray and ion hall thrusters. Electrical propulsion systems offer high specific impulse, but low thrust. Resistojets work similarly to cold-gas systems, but heat the exiting inert gas producing high specific impulse. Electrospray ionizes droplets of fluid and ejects them through fine nozzles. While ion-hall thrusters create an ionized plasma of charged particles that are ejected using a magnetic field. Currently there are no propulsion systems that offer high specific impulse with an Isp of 200 to 450 s, but that can fit in a CubeSat form-factor without requiring high storage pressures or posing other safety concerns.

A compelling alternative is to electrolyze water into hydrogen and oxygen on-demand using Polymer Electrolyte Membranes and produce high thrust through combustion. PEM electrolyzers offer the highest efficiency among electrolyzer technologies, reaching 85-90 %. They are simple devices, containing no moving parts, are clean and quiet. Storage of water minimizes launch safety concerns and does not require being stored at high pressures. The system can offer specific impulse of 360-420 s and at high thrust, albeit in a pulsed detonation mode. However, major challenges remain, including preventing the water from freezing when the spacecraft passes through eclipse and for efficient separation of water from hydrogen and oxygen in a microgravity environment, well beyond earth's gravity well.

Our proposed solution utilizes a spacecraft centrifuge controlled using reaction wheels that would automatically separate the water from hydrogen and oxygen gas, enabling operation well beyond Earth's gravity well. Our studies show that the system can be assembled almost entirely using commercial subsystems and components. The water contains salts, such as lithium chloride, that enable lowering the freezing point to -10 ^{o}C to -80 ^{o}C. It is critical for PEM electrolyzers to use liquid water, otherwise, components such as the membrane or gas exchanger get damaged. In addition, such an approach prevents pipes and pumps from freezing, which prevents mechanical/structural damage. The approach also reduces requirements on an active thermal control system. An additional benefit is that by lowering the operating temperature, we increase the life of the PEM electrolyzer by reducing catalyst degradation rates [14]. Enabling the spacecraft to operate well below 0 ^{o}C allows for using this approach for outer solar system exploration. Using this approach, we show a compelling pathway towards realizing a CubeSat system for interplanetary exploration.

In this paper, we first review state-of-the-art propulsion systems for CubeSats in Section 2, followed by presentation of the proposed Photo-Voltaic Electrolysis Propulsion System (PVEPS) in Section 3. This will include a preliminary design, system specification and overview of the concept. In Section 4, we present laboratory experiments performed to test some of the critical enabling technologies for PVEPS. This includes demonstration of PEM electrolyzers for production of hydrogen and oxygen on demand and the lowering of the freezing point using salts, followed by discussion in Section 5, conclusions and future work in Section 6.

2. RELATED WORK

Previously demonstrated propulsion systems for CubeSat have relied on low specific-impulse technologies. For example, the Can X-2 mission [4], a 3U CubeSat, flew a liquid sulfur hexafluoride cold gas thruster, which attained an I_{sp} of 50 s and a total ΔV of 2 m/s, where ΔV refers to the measure of impulse needed to perform a maneuver. More recent missions that will use cold gas for propulsion include the MarCo Mission [1] where a pair of CubeSats will flyby Mars to act as a communication relay during Entry, Descent and Landing (EDL) to the Mars Insight lander. The propulsion uses R-236fa refrigerant with a specific Impulse of 40 s and a wet mass of 3.5 kg.

Solid rocket motors have been proposed for CubeSats due to their overall simplicity, long shelf life and technology maturity. The smallest of these rocket motors include ATK's Star 3 motor [5] which was evaluated for CubeSats by the Aerospace Corporation [6]. The motor has a diameter of 8 cm, a length of 29 cm, a loaded mass of 1.16 kg, and can provide a 3 kg satellite with 620 m/s of ΔV.
Moreover, solid rockets are difficult to throttle, produce vibration and expend all of their propellant at once which poses challenges when using them for performing complex maneuvers. However, their high ΔV and thrust are particularly useful when trying to achieve orbit insertion. Increased maneuverability is achieved by using actuators to move a heavy mass within the craft [6]. By moving the mass, the system achieves yaw and pitch control.

Busek's electrospray propulsion system is baselined for LunaH-Map, a 6U spacecraft led by Arizona State University, that will be dropped off by the Space Launch System (SLS) and get into an insertion orbit around the Moon, obtaining neutron spectrometer readings of water-ice at the Lunar south pole [3]. Busek's RF-Ion thrusters are baselined for the Lunar-Ice Cube mission led by Moorehead State University is also set to orbit the Moon and obtain evidence of water-ice at the poles using an infrared spectrometer [2].

Another CubeSat propulsion system with much promise is Univ. of Michigan's CubeSat Ambipolar Thrusters (CAT) [7]. CAT is another form of plasma thruster that uses a permanent helicon magnet to accelerate plasma from a nozzle. The system uses water or iodine as fuel. This system occupies a relatively small volume and requires low power while producing 2 mN of thrust for 10 W. Interplanetary missions from Low Earth Orbit have been been proposed. Efforts are underway to develop a 3U LEO demonstrator. These electrical propulsion systems will enable significant maneuverability and promise high ΔV of several hundred m/s or more compared to cold-gas but offer low thrust. Increased thrust can be achieved by generating more power using large deployable solar panels, but this adds complexity to the CubeSat system.

Early work in electrolysis propulsion started at Lawrence Livermore National Labs in partnership with AFRL [15]. A system was devised that used PEM electrolyzers to produce hydrogen and oxygen and offered an I_{sp} of 400 s. These system required between 50 and 200 W. Even higher I_{sp} was projected using hybrid systems that contained arcjets and electric thrusters.

A water electrolysis propulsion system has been proposed by Zeledon and Peck [8] for a 3U CubeSat. The electrolysis propulsion occupies 2U of the 3U spacecraft. The electrolysis propulsion system occupies most of the volume up to 2U and leaves about 1U of the space for payload and other components. Zeledon and Peck [8] evaluated several methods for electrolysis including using potassium hydroxide (KOH) as an electrolyte and where the electrodes (cathode and anode) are made of nickel and zinc mesh strips. They also compared this to PEM electrolyzers that contain a platinum catalyst at anode and cathode sandwhiched between nafion proton-exchange membranes. PEMs were found to have higher efficiency.

The thrusters operate in a pulsed mode. A 1 liter propellant tank can provide about 1000 pulses and the average ΔV for each burst for this system is 1.9 m/s [8]. Separation of electrolyzed gases from the liquid water is achieved by constant spin of the spacecraft. A centrifugal force generated by constant spin of the CubeSat naturally separates the water from product gases. The system does not separate oxygen and hydrogen gases upon electrolysis. The hydrogen and oxygen gases are collected in the same chamber and then released into the combustion chamber when the desired pressure is achieved.

The spacecraft generates approximately 5N of thrust and an approximate impulse of 0.6 Ns per pulse. The spin in the spacecraft is established after separation from the mother vehicle by magnetic torquers embedded in the solar panels. The spin state of the spacecraft before separation is prevented by the nature of the P-POD deployer which latches onto the CubeSat until launch. Since the spacecraft makes use of magneto-torquers for generating spin about its thrust axis, this design is not going to work outside the Earth's magnetic field. In addition, without the use of at least one reaction wheel, the system will have challenges spinning. The concept is only limited to missions up to Geostationary Earth Orbit (GEO) orbits. In order to make CubeSat missions possible beyond Earth's magnetic field, an alternative solution is required.

A second approach is being developed by Tethers Unlimited and is called Hydros [8]. It is supplied with water which is electrolyzed into hydrogen and oxygen on-orbit to deliver the required thrust. Hydros is currently at technology readiness level (TRL)-5. It is designed to be available in 0.5U and 1U configurations, delivering up to 0.8 N of thrust at 300 s of I_{sp}. This design also comes with an Attitude Control Module which uses the electrolyzed hydrogen and oxygen from water. The lower value in thrust is clearly evident from the fact that a part of the electrolyzed gases are supplied to the Attitude Control Module. It makes use of a bipropellant micro thruster which is capable of both pulsed hot and cold gas operation.

What is desired is a propulsion system that offers both high thrust and high ΔV, with the ability to throttle and scale-up based on interplanetary mission needs. Electrolysis of water into hydrogen and oxygen that is combusted offers a promising solution to all these propulsion challenges, but requires additional capabilities than what is described here for it to be applicable for interplanetary missions. In an interplanetary mission, long duration operations are required with the ability to stop and start after long intervals and withstand cold storage temperatures (well below 0 ^{o}C).

3. PHOTO-VOLTAIC ELECTROLYSIS PROPULSION

The proposed photovoltaic electrolysis propulsion system is shown in Figure 2. The system obtains its energy from triple junction solar cells. The power input is maximized using a peak power point tracker and is passed to a DC to DC convertor.

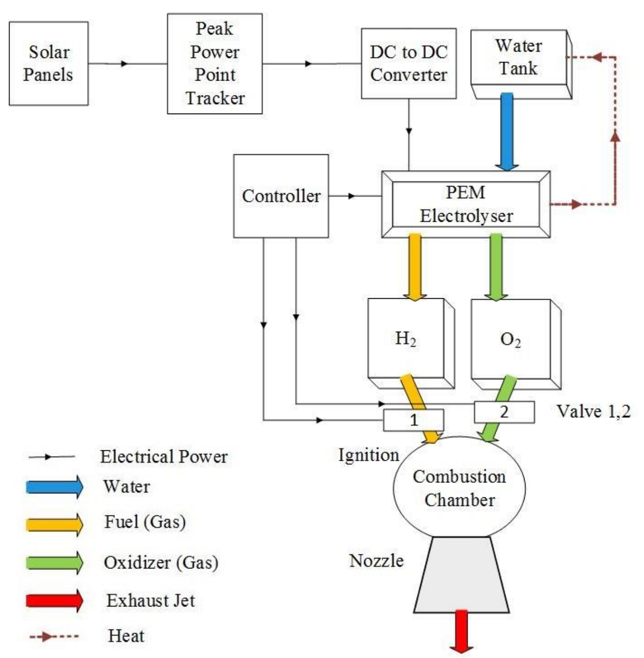

Figure 2. Schematic of Photovoltaic Electrolysis Propulsion System.

The power may be stored in a battery or fed directly to a PEM electrolyzer situated inside a water tanks. A controller sets the operating voltage of the electrolyzer to maximize hydrogen and oxygen production rates. The electrolyzer splits the water molecules into hydrogen and oxygen at the anode and cathode, respectively. Because the craft will be in microgravity, the water and gas will not readily separate and collect as on Earth. Therefore, the entire propulsion system is spun at rates of 1 rpm or more, ensuring that the water remains at the outer edges and the hydrogen and oxygen gas separate from the water. The collected hydrogen and oxygen is stored in a plenum tank. The controller then feeds the oxygen and hydrogen and combusts the gas mixture.

The propulsion system (Figure 3) would consist of a propellant tank, 6 PEM electrolyzers, oxygen and hydrogen storage tanks, a combustion chamber and a convergent divergent nozzle. The remaining volume was allocated for payload, battery and other equipment. Table 1 shows the mass and volume budget for the proposed propulsion system. The individual parts of the system are explained below.

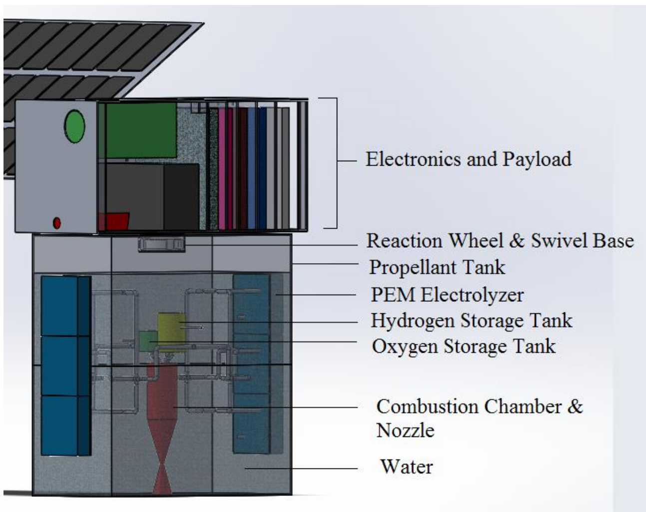

Figure 3. PVEPS System Concept Layout

The expelling gas is directed through the rocket nozzle to produce thrust. The system is designed so that the oxygen and hydrogen are generated on demand. When there is limited power, the propulsion system may be operated in a pulsed mode, where the oxygen and hydrogen tanks are filled and combusted periodically. Alternately, if large, deployable panels can provide 60-90 W, then the system may be operated continuously. A layout of the proposed system is shown for a 6U, 12 kg CubeSat with a 7.8 kg of propellant.

Table 1. Spacecraft Mass and Volume Budget

Component		Mass (kg)	Volume (L)
Propulsion	Propellant	7.8	7.8
	PEM Electrolyzer	0.1	0.2
	Control Electronics	0.1	0.2
Structure		2	0.8
Payload, Computer, ACDS & Comms.		2	1.0

Propellant Tank

The propellant tank takes up 7.8 L. It would be surrounded by a chassis made from 5052-H32 sheet aluminum. The propellant tank would be made from 6061-T6 Aluminum. The entire propulsion system would be placed inside the propellant tank. This would also assist in the flow of heat from the combustion chamber to the green propellant surrounding it, thereby preventing the thrust chamber from overheating.

PEM Electrolyzer

Each PEM electrolyzer measures 5.4 × 5.4 × 1.7 cm^3 and weighs 20 g. A total of six units are located strategically inside the propellant tank. They are divided into two sets and are placed opposite to each other along the length of the propellant tank. They are aligned in such a way that all the hydrogen and oxygen outlets stay on the same side in order to reduce the complexity of the pipelines. The power for these Electrolyzers comes from a battery which is located in the payload segment.

Storage Tank

Hydrogen and Oxygen are stored separately to increase the safety of the system by preventing premature combustion in the cylindrical storage tanks located near the center of the propellant tank. They are constructed of 1mm thick Aluminum 6061-T6. The Hoop Stress equation for a cylinder is used to determine the minimum thickness for the storage tank and is given by:

$$\sigma_\theta = \frac{Pr}{t} \tag{1}$$

where σ_θ is the Hoop Stress, P is the Internal Pressure, r is the mean radius of the cylinder and t is the wall thickness. Assuming the value of the storage pressure at 6 bar and with a 5-fold safety margin, the wall is set to 1mm. Both the storage tanks are 2.5 cm in diameter. The hydrogen tank is 3 cm long. The outlets from all the electrolyzers are connected to the inlet of the respective storage tanks through pipelines.

Thrust Chamber

The thrust chamber is made of Ti-6Al-4V (titanium) with a thickness of 1 mm to ease the purpose of machining. This is also derived from the computation shown earlier in this section. The outlets from the storage tanks are connected to the inlets of the combustion chamber where combustion occurs when required. The combustion chamber is connected to a convergent divergent nozzle which expands the hot gases to produce thrust. The design parameters of the combustion chamber and the de Laval nozzle are computed from the system performance explained later in this section.

Swivel Base and Reaction Wheel

The payload section and the propulsion system are connected by a swivel base which aligns with the axis of the thrust chamber and is also located close to the maximum axis of inertia. A reaction wheel is located inside the swivel base which ensures that the propulsion system of the CubeSat spins constantly at a rate of 2 rad/s. The swivel base ensures that the payload section remains rigid and the propulsion section spins due to the effect induced by the reaction wheel. A Blue Canyon Tech's micro reaction wheel was selected for this purpose and it operates at 1.7 W [10]. This can be seen on Figure 4.

System Operation

Once the 6U CubeSat is deployed from the mothership, the onboard motherboard springs to life. It commands the reaction wheel, placed in the swivel base to rotate the propulsion system at a rate of 2 rad/s. As soon as the desired rotational speed is achieved, the propellant in the system goes through the inlet of the PEM electrolyzers. The centrifugal force caused by the spin of the CubeSat helps in separating water from gas in the PEM electrolyzer.

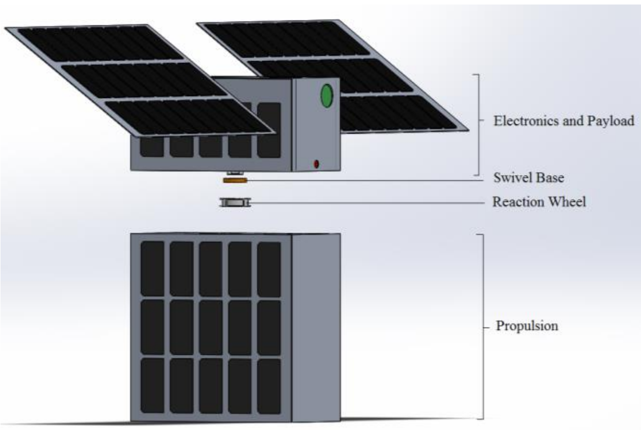

Figure 4. Major segments of the proposed concept.

Then, the propellant, which is a brine (salt) solution is electrolyzed into hydrogen and oxygen gases. These gases are collected in the storage tanks located at the center of the system. Once the desired amount of hydrogen and oxygen gas is available, an electronic valve lets these gases enter the thrust chamber. The onboard computer triggers the spark igniter and combustion of the gases begins. These hot gases are then expanded in the convergent divergent nozzle and expelled to produce thrust. Meanwhile, more propellant is electrolyzed and collected in the storage tanks. A second pulse is produced when enough hydrogen and oxygen gas has been collected.

When a large amount of the propellant is consumed, the rotation of the propulsion system ensures that the remaining propellant stays on the periphery of the propellant tank thereby ensuring a continuous flow into the Electrolyzer inlet. This spin also helps to reduce the shift in center of gravity of the system.

The biggest concern that needs to be addressed in the operation of the system is maintaining the liquid state of the propellant, since the PEM electrolyzer cannot function if the propellant inside the tank freezes. A possible solution to this problem is thermal shielding. An alternative solution is freezing point depression of water by the use of additives.

Freezing Point Depression

The freezing point of water can be depressed by adding a salt or solvent. The freezing point depression ΔT_f is given in equation (2) and is a colligative property of the solution and for dilute solutions is found to be proportional to the molal concentration (c_m) of the solution and K_f is the Freezing Point Depression Constant.

$$\Delta T_f = K_f c_m \tag{2}$$

4. SYSTEM PERFORMANCE

Metrics to evaluate the performance of propulsion systems currently do not capture all of the evaluation criteria necessary at CubeSat 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. The characteristics of a successful propulsion system at a CubeSat scale are [8]:

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

Photovoltaic Electrolysis Propulsion System (PVEPS) satisfies all the above criteria.

Specific Impulse (I_{sp})

Analysis of the combustion and flow through the nozzle using both theoretical equations and finite-volume CFD modeling shows that the specific impulse of the system is in the range of 360s – 420s . For a control volume of a thrust chamber, the steady flow energy equation can be given as:

$$\frac{\dot{Q} - \dot{W}_e}{\dot{m}} = \left(h_e + \frac{V_j^{\,2}}{2} + g z_e\right) - \left(h_c + \frac{V_c^{\,2}}{2} + g z_c\right) \tag{3}$$

Where, $\dot{m}$ is the mass flow rate through the nozzle, h_c is the enthalpy of the gas in the chamber and h_e is enthalpy of the gas at the exit of nozzle. Since the nozzle is of fixed construction, it does no work ($\dot{W}_e = 0$). Considering no heat transfer, viz. an adiabatic vent, we have $\dot{Q} = 0$. Further, the change of the gravitational potential energy g$(z_e - z_c)$ is small and could be assumed as negligible. The gas in the chamber can be considered stationary (Vc = 0). Equation 4 for the control volume therefore becomes:

$$\frac{V_j^{\,2}}{2} = h_c - he \tag{4}$$

In Photovoltaic Electrolysis Propulsion System (PVEPS), we use hydrogen as the fuel and oxygen as the oxidizer, which combine to form water. The enthalpy of formation of water vapor, or equivalently in this case, the enthalpy of combustion, is -241.82 kJ/mole. Upon exit, the water vapor will condense, due to extreme temperature change, and the enthalpy of condensation of water is 40.65 kJ/mol. Plugging these values into equation 4, we have the exhaust jet velocity V_j = 4720 m/s. This means the maximum possible I_{sp} from the system is 482 s. This is the theoretical specific impulse of a rocket operating at steady state. For a very short pulse this can be lower than 50%, and with pulses of 0.45 s, it can be around 75% to 88% [11]. This means the specific impulse available for the given system is between 362 s and 424 s.

At this efficiency, using the Tsiolkovsky rocket equation (5), the ΔV produced by the system for a 12 kg spacecraft with 7.8 kg of propellant is around 3,700 m/s (I_{sp} 362 s) and 4,400 m/s (I_{sp} 424 s).

$$\Delta V = V_j \times \ln \frac{1}{R_m} \tag{5}$$

where, V_j is the exhaust velocity of the hot gas and R_m is the mass ratio of the spacecraft.

A quantitative meaning to this can be derived from the fact an Earth escape from Geostationary Transfer Orbit (GTO) requires nothing more than 800 m/s [12]. This gives ample scope to enable a lunar transfer orbit by exploiting the weak stability boundary in the Earth-Moon system. Table 1 gives the ballpark values of ΔV required from Low Earth Orbit to Lunar Orbit or the Earth-Moon Lagrange points.

Nozzle Design Analysis

A nozzle converts thermal energy into kinetic energy. It facilitates the conversion of high temperature, high pressure gas, within the combustion chamber into high velocity jets with lower pressure and temperature. The design of the nozzle ensures that the hot gas expands which results in lower pressure and higher velocity. Nozzle throat is the minimum flow area between the divergent and convergent section. The nozzle design parameters for the system can be computed from the following equations:

$$P_t = P_c \left(1 + \frac{k-1}{2}\right)^{\frac{-k}{k-1}} \tag{6}$$

$$T_t = \frac{T_c}{(1 + \frac{k-1}{2})} \tag{7}$$

where, P_t is the pressure at nozzle throat, P_c is the pressure inside the combustion chamber, k is the specific heat ratio, T_t is the temperature at nozzle throat, T_c is the temperature inside combustion chamber

We have specified the system to operate at a pressure of 6 bar and combustion would occur at a temperature of 1300 K. Assuming the specific heat ratio of water vapor to be 1.32, the above parameters have been computed to be P_t = 3.25 bar and T_t = 1120 K. Using the formula for Nozzle throat area we have:

$$A_t = \frac{q}{P_t}\sqrt{\frac{R \times T_t}{M \times k}} \tag{8}$$

where, q is the propellant mass flow rate, R is the universal gas constant, M is the molecular mass of water vapor.

Using this data, the combustion chamber can be designed. Considering a mass flow rate of 1 g/s, as expected for the electrolyzed propellant for one pulse, the nozzle throat diameter is calculated to be D_m = 78 mm. The convergent cone section has a half angle between 12 to 18 degrees. The divergent half angle is almost a standard of 15 degrees as it is a compromise on the basis of weight, length and performance. The values are summarized in Table 2.

Table 2. Nozzle Design

Mass Flow Rate (g/s)	1
Specific Heat Ratio	1.32
Chamber Pressure (N/m^2)	6×10^5
Nozzle Throat Pressure (N/m^2)	3.2×10^5
Chamber Temperature (K)	1300
Nozzle Throat Temperature (K)	1120
Nozzle Throat Area (m^2)	1.9×10^{-6}
Nozzle Throat Diamter (mm)	0.78

Combustion Chamber Design Analysis

The combustion chamber serves as an envelope to retain the gases for a sufficient period such that complete mixing and combustion of the propellants is ensured. The characteristic length (L^*) of the chamber is a useful parameter that relates nozzle throat area and combustion chamber volume based on residence time of the propellant for complete combustion. It is given by:

$$L^* = \frac{V_c}{A_t} \tag{9}$$

$$V_c = A_1 L_1 + A_1 L_c (1 + \sqrt{A_t / A_1} + A_t / A_1) \tag{10}$$

where, V_c is the volume of the combustion chamber, L_1 is the length of the cylinder, L_c is the length of the conical frustum, and A_1 is the area of the cylindrical chamber.

The value of L^* is chosen from available databases for specified propellant constituent combinations. The volume of the combustion chamber, $V_c = 5 \times 10^{-5}$ m^3. The calculated values are shown in Table 3.

Table 3. Combustion Chamber Design

Combustion Temperature (K)	1300
Chamber Pressure (N/m^2)	6×10^5
Chamber Volume (kg/m^3)	4.5×10^{-5}
Chamber Diameter (m)	0.025
Chamber Area (m^2)	4.9×10^{-4}
Chamber Length (m)	0.05
Nozzle Throat Diameter (mm)	0.78
Nozzle Throat Area (m^2)	4.8×10^{-7}
Chamber Contraction Ratio	9.8×10^{-4}
Converging Cone Frustum Length (m)	0.041

5. EXPERIMENTS AT LOW TEMPERATURE

Laboratory experiments were conducted to justify the use of salt solutions as additives for the water used with the PEM electrolyzer. Our studies show that this is a promising approach. These experiments were conducted at different temperatures, particularly below freezing to determine the performance and efficiency of the PEM electrolyzer. The experiments are presented in detail below.

The principle for all these experiments is similar. When a direct current is applied to a PEM electrolyzer, water is electrolyzed into gaseous hydrogen and oxygen. The rate at which electrolysis occurs depends on the input current and voltage applied to the PEM electrolyzer. The experimental setup is shown in Figure 5. A tray is filled with 2 liters of colored water and placed on a level surface. Each of the graduated cylinders is filled to the brim with water. They are then inverted with a cap on top to prevent the water from spilling. These graduated cylinders are placed, inverted, into the water tray such that a part of them is immersed in water. Now, the caps are removed and the graduated cylinder is held in place with the help of a burrete stand and clamps. Silicon tubing is connected to the ports on the PEM electrolyzer. The tubing connected to the hydrogen inlet is sealed. The tubing connected to the water inlet is connected to a check valve. The other end of this check valve (inlet) is connected to a syringe. The tubing connected to the hydrogen and oxygen outlets are connected to each of the inverted graduated cylinders. The power for the PEM electrolyzer is provided by a DC power supply.

The entire setup is held at standard room temperature and pressure. The syringe is filled with distilled water. Water from the syringe is forced into the electrolyzer by the piston, since the force of gravity is not sufficient to overcome the capillary force in the electrolyzer. Readings of water level from the graduated cylinder are noted. Now, the DC power supply is set to a voltage reading of 2 V. Once the Electrolyzer is connected to the DC power supply, bubbles can be seen collecting on both graduated cylinders. The process is repeated with salt water held at low temperatures inside a freezer.

Experiment Results

Figure 6 shows the maximum hydrogen production rate achieved using a single electrolyzer cell for different temperature and salt solutions. We compare results for sodium chloride and lithium chloride solutions. Sodium chloride at 10 % solution was discounted because it freezes at -5 ^{o}C and was not adequate for our needs. The results show that low concentrations of lithium chloride salt can be used to lower the freezing point and achieve comparable hydrogen production rates of distilled water at 25 ^{o}C.

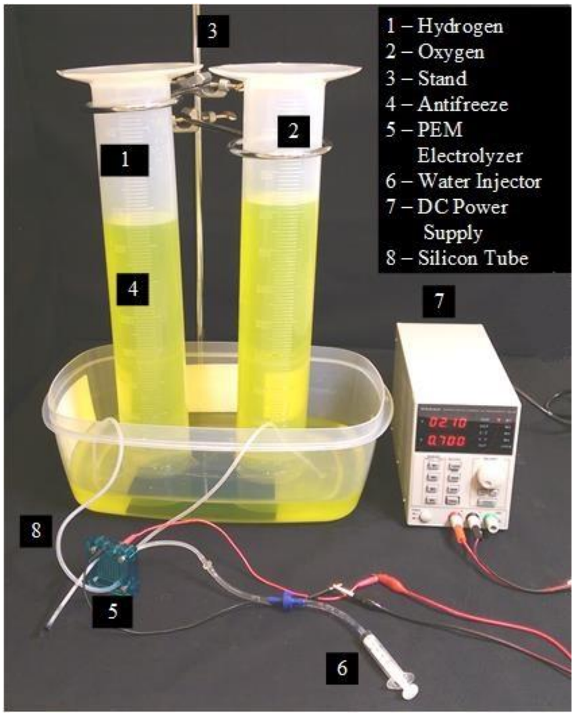

Figure 5. Electrolysis Experiment Setup.

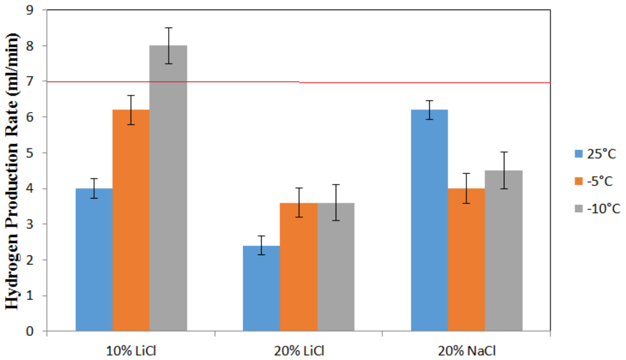

Figure 6. Comparison of Maximum Hydrogen Production Rates. Red line indicates max hydrogen production rate at 25 ^{o}C using distilled water.

Increasing the salt concentration increases the voltage required and this limits the power that could be transferred through the electrolyzer which in turn limits the hydrogen production rate. Figure 7 shows the hydrogen output for varying voltage and temperature. With a fixed concentration, the operating voltage used to achieve peak hydrogen production remains constant and nearly independent of temperatures below freezing. However, as the temperature gets below freezing, decreasing the freezing point as shown, increases the hydrogen production rate for the lithium chloride salt solution.

Figure 8 shows that with increased salt content and increased operating voltage for peak hydrogen production results in lower power input to the system. This is to be expected - as the kinetic energy of the water solution is decreased, it is less able to result in catalyzing the electrolysis process. To compensate for these factors would require more electrolyzers.

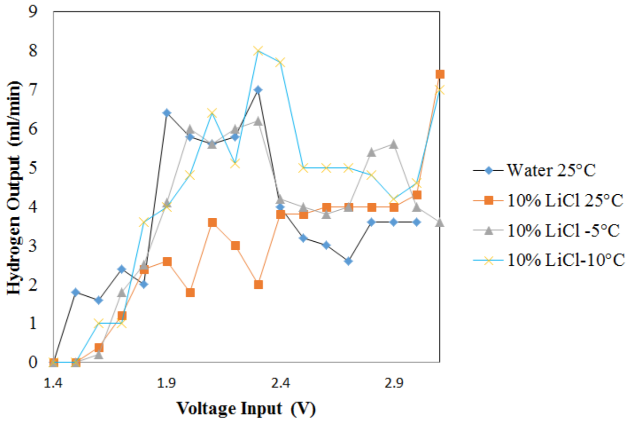

Figure 7. 10% Lithium Chloride Solution as Electrolyte at Different Temperature

These results show that an electrolyzer utilizing a lithium chloride solution can operate at -10 °C without any performance loss. For even lower temperatures, we expect a steady reduction in hydrogen production rate due to increased operating voltage. For even lower temperatures, we will require an increased number of electrolyzers to match the hydrogen production of distilled water at 25 °C.

6. System Comparison & Discussion

Feasibility analysis suggests that the proposed PVEPS is superior to other propulsion options available for CubeSats because it provides a much higher ΔV and is safe (as shown in Table 4). Though not many concepts have been planned to meet the requirements of high ΔV missions, there has been considerable research going on to achieve it.

One of these attempts has been mentioned earlier being developed by Zeledon and Peck 2011 [8]. Zeledon and Peck's system is designed to perform orbit raising maneuvers. A scaled up version of this system to a 12 kg CubeSat will still not produce the ΔV that can be achieved using PVEPS. The system developed by Peck and Zeledon makes use of magnetic torquers which provide the spin required for the CubeSat in order to separate the electrolyzed gases from water. These magnetic torquers utilize the Earth's magnetic field to generate the required torque to rotate the spacecraft. If this system was scaled up to 6U, it would still be restricted to navigating within the earth's magnetic field. Since the PVEPS has a reaction wheel on board which produces the required spin on the spacecraft for gas separation, it can be deployed for missions that operate well beyond the earth's gravity well.

Thermal insulation is another important consideration when designing these systems. Since both the systems, require water for electrolysis it is critical that water remains a liquid during operations. Peck and Zeledon, required thermal insulation and requires a method to keep the junction temperature higher than 0°C. This requires power from the battery or solar cells and also adds mass to the CubeSat, implying increased complexity.

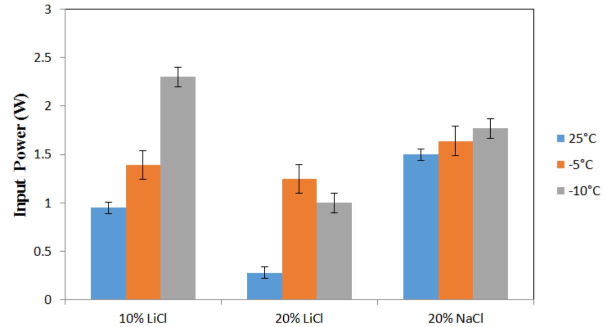

Figure 8. Comparison of Power Input for Maximum Hydrogen Production Rates

Table 4. Comparison of CubeSat Propulsion Systems

System	ΔV (m/s)	Thrust (N)	Safety & Thermal
Photovoltaic Electrolysis Propulsion System (H_2O)	4000	8.5	Green propellant Separate H_2 and O_2 tanks No heat required
Electrolysis Propulsion By Mason Peck and Zeledon (H_2O) [8]	850	5	Green Propellant Same H_2 and O_2 tank Requires heat
CubeSat Modular Propulsion System (Hydrazine) [13]	550	4	Highly toxic propellant Requires heat
Cold Gas Thruster System (Nitrogen)	20	1.5	Inert Propellant No heat required

Table 5 lists the power required in terms of keeping a 12 kg, 6U CubeSat at 297 K. It is clearly evident that at certain conditions of the mission, the heat energy required is abnormally high, which can make the use of this system for such missions meaningless. In case of the PVEPS, the freezing point depression by the use of additives in water helps resolve this issue. Not only does this save additional mass from being inserted into the system, but also ensures that more propellant can be carried which results in higher ΔV.

Table 5. Heat Energy Requirements for 6U CubeSat at LEO

Condition	Panel Temp. (K)	Heat Energy Required (W)
One Side Illuminated	260	25
Three Sides Illuminated	290	1

Three Sides Illuminated, Albedo and Infrared	320	-18
Eclipse	170	80

Further, Zeledon and Peck's system does not separate hydrogen and oxygen after electrolysis. The electrolyzed gases are collected in the same chamber where they are stored before combustion. Premixing of hydrogen and oxygen poses a safety risk, particularly because we have a spinning spacecraft. This may result in static charge buildup that can result in an unpredictable spark discharge which would risk an explosion. While efforts could be made to prevent static discharge, it is easier to avoid this risk by not mixing the propellants.

The other closest attempt of making a CubeSat propulsion system to deliver higher values of ΔV is CubeSat Modular Propulsion System (MPS) by C. Carpenter, D. Schmuland, et al. (2013) [13]. This system provides thrust by four 1 N rocket engines. The total mass of the propulsion system is 3.2 kg including 1.2 kg of propellant. This system occupies $10 \times 10 \times 23$ cm^3 and operates in a temperature range of 5 to 50°C. This system makes use of Hydrazine propellant with a thrust of 2.79 N impulse of 0.004 N per thruster. This system was designed for specific missions such as orbit maintenance and attitude control. The ΔV and thrust provided by this system are not sufficient for orbit raising.

7. CONCLUSION AND FUTURE WORK

The proposed Photo-Voltaic Electrolysis Propulsion System shows great promise. The system uses water to generate hydrogen and oxygen, in-situ, using photovoltaics. The system is calculated to offer a ΔV of upto 4,400 m/s for a 6U interplanetary CubeSat. The results of the experiments and early design studies show that with sustained research, the technology is ready for a demonstration system. Through these studies, we have laid the foundation for the system. Our proposed system brings together several innovations that improve the performance and safety of the propulsion system. The use of separate storage tanks for Hydrogen and Oxygen improves the functionality of the system. The concept of spinning only the propulsion section with respect to payload and electronics by use of micro reaction wheel makes the approach practical for interplanetary missions. Utilizing the concept of freezing point depression for storing propellant in CubeSats enables them to be operated for a wide range of environmental conditions. Our efforts are now focusing on developing a laboratory prototype of the concept in preparation for a flight demonstration.

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BIOGRAPHY

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