Photovoltaic Electrolysis Propulsion System

By

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ABSTRACT

CubeSats are a newly emerging, low-cost, rapid development platform for space exploration research. They are small spacecraft with a mass and volume of up to 12 kg and 12,000 cm^3, respectively. To date, CubeSats have only been flown in Low Earth Orbit (LEO), though a large number are currently being designed to be dropped off by a mother ship on Earth escape trajectories intended for Lunar and Martian flyby missions. Advancements in propulsion technologies now enable these spacecraft to achieve capture orbits around the moon and Mars, providing a wealth of scientific data at low-cost. However, the mass, volume and launch constraints of CubeSats severely limit viable propulsion options.

We present an innovative propulsion solution using energy generated by onboard photovoltaic panels to electrolyze water, thus producing combustible hydrogen and oxygen for low-thrust applications. Water has a high storage density allowing for sufficient fuel within volume constraints. Its high enthalpy of formation provides more fuel that translates into increased ΔV and vastly reduced risk for the launch vehicle. This innovative technology poses significant challenges including the design and operation of electrolyzers at ultra-cold temperatures, the efficient separation of the resultant hydrogen and oxygen gases from liquid water in a microgravity environment, as well as the effective utilization of thrust to produce desired trajectories.

Analysis of the gas combustion and flow through the nozzle using both theoretical equations and finite-volume CFD modeling suggests an expected specific impulse of

360 s. Preliminary results from AGI's Satellite Toolkit (STK) indicate that the ΔV produced by the system for an 8kg CubeSat with 6kg of propellant in a LEO orbit (370 km altitude) is sufficient for an earth escape trajectory, lunar capture orbit or even a Mars capture orbit. These results suggest a promising pathway for an in-depth study supported by laboratory experiments to characterize the strengths and weaknesses of the proposed concept.

To my parents Krishna and Padma Muneendra Pothamsetti

ACKNOWLEDGEMENTS

Firstly, I want to express my biggest accolade to my Chair, Guru and Mentor Dr. Jekan Thanga. His guidance, knowledge and support has driven me all through my work in the laboratory and pushed me to learn more outside it by allowing me to get a very wide range exposure in PEM electrolyzers, CubeSats, and green propulsion systems for space missions and access to STK (Systems Tool Kit) which is very tough to find. I feel lucky to have a chance to work under such an innovative professor. I thank him for patiently guiding me throughout my work and career.

I have been amazingly fortunate to have Professor Werner J.A. Dahm, the Founding Director and Chief Scientist (SDSI) and ASU Foundation Professor of Aerospace & Mechanical Engineering to be my co-chair. Most importantly, this would have not been possible without Dr.K. N. Solanki, Assistant Professor, School of Engineering of Matter, Transport and Energy at Arizona State University, who accepted to be co-chair for my research work from day one. I am deeply grateful to my advisers for their timely support in all matters. I would like to thank Dr. Eric Adamson who patiently went through my thesis literature and proofread it.

I would like to thank the guidance offered by my colleagues and friends Francesco Maria Testi, Laksh Raura and Robert Amzler for helping me with the SolidWorks model and finish up experiments in the laboratory. Lastly, I want to thank my friends and folks working at the SpaceTREx Laboratory who motivated me throughout my research.

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CHAPTER 1

INTRODUCTION

1.1 Background

On October 4th 1957, the Soviet Union launched the first satellite, Sputnik, into Space. Since then, there have been numerous launches. According to the UCS Satellite Database (www.ucsusa.org) there are 1265 operating satellites in orbit around the earth as of February 1st, 2015. CubeSats have formed an integral part of these statistics over the past two decades.

The origin of CubeSats lies with Prof. Bob Twiggs of Stanford University and Jordi Puig-Suari of CalPoly University. The idea was to develop a vehicle to support university level space education at very low costs. At its most fundamental level, the CubeSat can be defined as a discrete but scalable 1 kg, 10 cm x 10 cm x 10 cm cubic spacecraft unit, which is now commonly referred to as a 1U(nit) CubeSat. Figure 1 shows a CubeSat Structure. Since, CubeSats are scalable, larger systems are produced by combining these fundamental 1U units. To date, 6U systems have been proposed and up to 3U systems have been demonstrated in-orbit. The configuration of a 6U is typically a 3x3 structure.

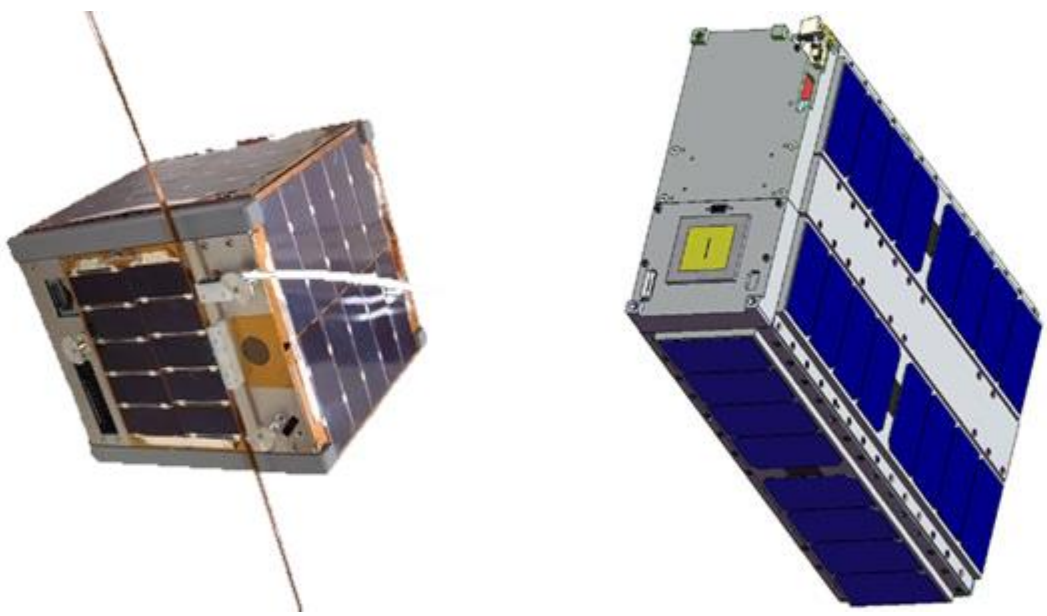


Figure 1 – Size Comparison of 1U and 6U CubeSat [1]

A CubeSat Design Standard [2] was introduced by CalPoly University in 1999, with a primary intention to reduce time requirements and cost of a satellite from concept to launch. A reduction in project management, engaging student labor with expert oversight, limited or no built-in redundancy and access to launch opportunities using standard launch interface has made this possible. The standardized mechanical interface and deployment technology between the launch vehicle and CubeSats makes them readily launched as secondary payloads. [3] This has reduced risk and minimizes demands on project resources for university researchers. The reduction in cost and the opportunity to study space with resources available at a University level has motivated many student groups to pursue CubeSat design and development. Since the introduction of the design standard, the number of CubeSat launches has spiked exponentially. Figure 2 shows the count of CubeSat launches over the past decade. One of the reasons for the spike in CubeSat launches in 2013 and 2014 is due to free launch opportunities available for university researchers.

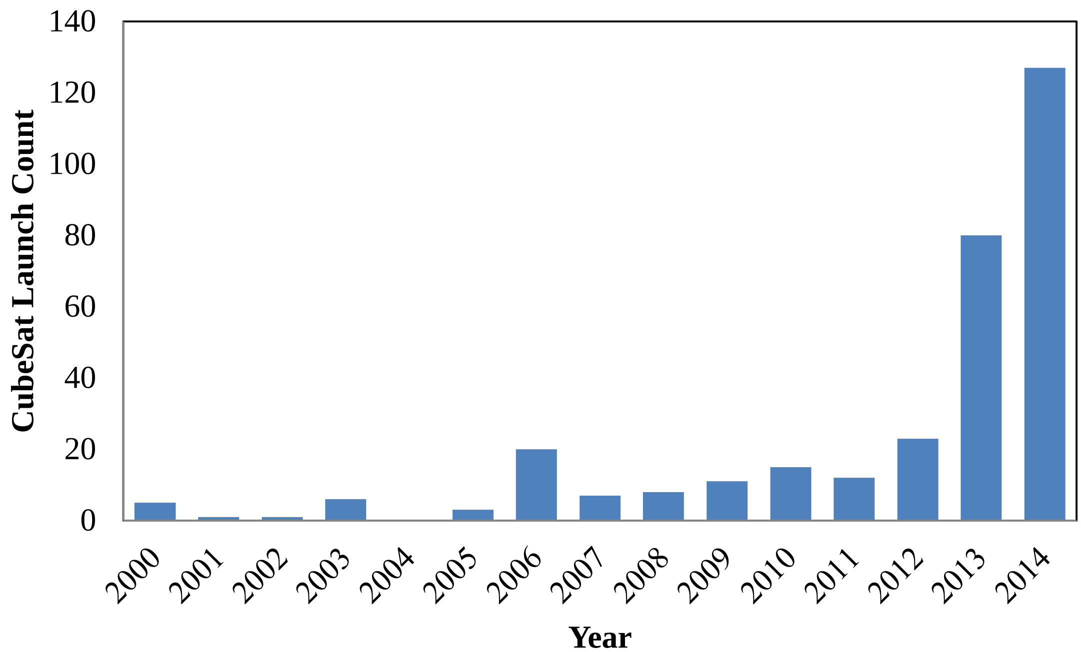


Figure 2 – Number of CubeSat launches annually since the inception of the CubeSat standard

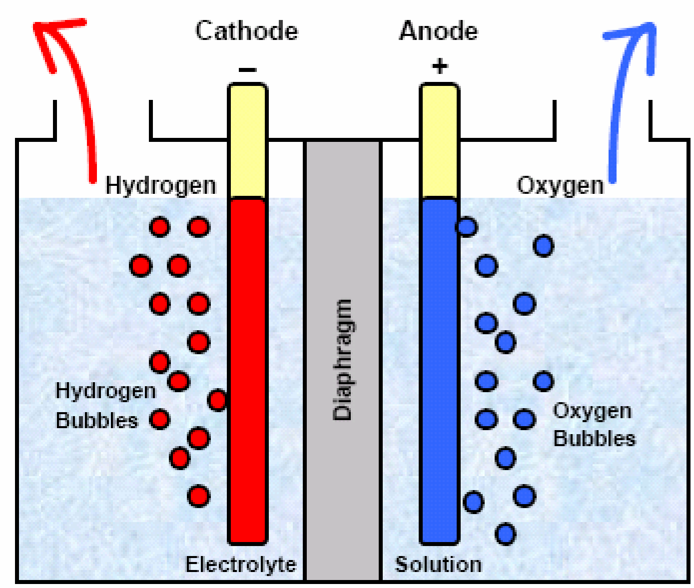
1.2 Problem Statement

For the most part, CubeSat missions have been confined to Low Earth Orbit (LEO). [3] The small volume and mass have restricted the use of propulsion systems. New, more complex missions will be possible if these small, affordable satellites can perform significant orbit raising.

Previously implemented propulsion systems at the CubeSat scale 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 50s and a total ΔV of 2m/s. ΔV refers to the measure of impulse needed to perform a maneuver.

A 3U CubeSat can barely accommodate a miniaturized solid-propellant rocket considering space requirements for payload and other hardware. The smallest of which is ATK's Star 3 motor [5], with a diameter of 8 cm, a length of 29 cm, and a loaded mass of 1.16 kg, can provide a 4 kg satellite with just over 330 m/s of ΔV. Moreover solid rockets are difficult to throttle and expend all their propellant at once which makes them unfit for the required mission. Such propulsion systems severely limit the type of orbital maneuvers possible, precluding multiple burns. Though pressurized vessels would offer an alternative to solid rockets, the CubeSat Design Standard limits such vessels over 1.2 atmospheres.

The solution requires being less complex, and one that can be fit into small sizes which is both feasible and functional. Electrolysis propulsion comes in handy in this scenario. It obtains energy from solar cells and operates on inert propellant - water in this case. This is also very a safe method, which does not require heavy propellant tanks or batteries for storing energy. It therefore can be fitted into CubeSat which can make much more complex missions a success. Here, in this report we shall deal with design configuration of the said propulsion system and their functioning in detail. Figure 3 shows a schematic of the electrolysis process.



Standard Electrolysis

Figure 3 – Standard Electrolysis Process [6]

When a current is passed in the above shown setup, water molecule dissociate into Hydrogen and oxygen ions. These ions combine within themselves to form gas molecules in the form of bubbles. Hydrogen gas is collected near the cathode and Oxygen gas is collected near the anode. This process of breaking down water into Hydrogen and Oxygen gas bubbles is termed as Electrolysis.

1.3 Scope

The focus of this thesis is to study electrolysis using energy from the sun to produce hydrogen and oxygen which can later be used to produce thrust when required. Using this principle, we shall design a compact propulsion system in accordance to the CubeSat Design Standards. The experimentation is designed as follows:

1. Freezing Point Depression of Propellant (Water)
2. Performance of a PEM (Polymer Electrolyte Membrane) Electrolyzer at Room Temperature
3. Performance of a PEM electrolyzer at Subzero Temperature
4. Impact of Brine Solution on the performance of a PEM electrolyzer
5. Impact of Brine Solution on the performance of a PEM electrolyzer at subzero temperature
6. Thrust and Estimations based on PEM electrolyzer Efficiency

1.4 Objective

The main objective of my thesis is to develop an electrolysis propulsion system which uses green propellant (colored water) and solar energy to produce thrust that can be fitted into a CubeSat for orbit raising and interplanetary missions. To come up with possible solutions for the challenges faced while designing and operating a system concept at extreme conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Water Rocket

In 1998, the Lawrence Livermore National Laboratory and the Air Force Research Laboratory (AFRL) collaborated on various technologies which became to be known as "Water Rocket". [7] It was chosen to be a collective name for different set of technologies that were integrated to offer new options for propulsion, power, energy storage and structure in a spacecraft. They had conceived at this time that low pressure water on the spacecraft is electrolyzed to generate, separate and pressurize gaseous hydrogen and oxygen which provides about 400 s of specific impulse (I_{sp}). It was also proposed that even higher specific impulse could be achieved by combining this with other advanced propulsion technologies, such as arcjets[8] or electric thrusters.

Since water is the propellant for the water rocket, it was therefore a medium for high energy density electrical energy storage. As the same propellant tank and fuel are used for both propulsion and energy storage, it allows for operational water allocation decisions to be made possible during the mission. Mass savings from subsystems with overlapping functionality and redundancy may be combined which is highly advantageous. Several key aspects of the Water Rocket are enlisted below:

- Use of micro gravity electro chemical stack design removes the need for moving parts
- Increase in ΔV due to lower mass requirements
- A range of thrust levels can be produced for gaseous Hydrogen as a propellant
- Water is nontoxic and may be stored at low pressure, minimizing hazards posed to launch vehicle.
- PEM electrolyzers, used to generate propellant in water rockets, may also be employed as fuel cells to generate electrical power
- Massive batteries in the system can be reduced which would improve the mass fraction of the Water Rocket

Major accomplishments of the Water Rocket include [7]:

- Preliminary design of a lightweight zero-g Electrolyzer with peak electric input power levels of 50 watt, 100 watt and 200 watts. The system was designed based on the 200 watt Electrolyzer and is capable of generating 100 watts of peak electrical output power.
- The Hamilton Standard static feed water Electrolyzer was reactivated for micro gravity environments. The objective of this unit was to allow hydrogen pressure to exceed water pressure using an electrochemical hydrogen pump.

- New gaseous Hydrogen and oxygen thrusters were developed using a NASA LeRC iridium coated rhenium (Ir/Re) for an initial thrust rating of 0.25 lbf, but also capable of operating to thrust levels upto 5lbf.
- The details of the trade study conducted on the conceptual design of 2000 psi Static Feed Water Electrolyzer is as follows:

2.2 PEM Electrolysis

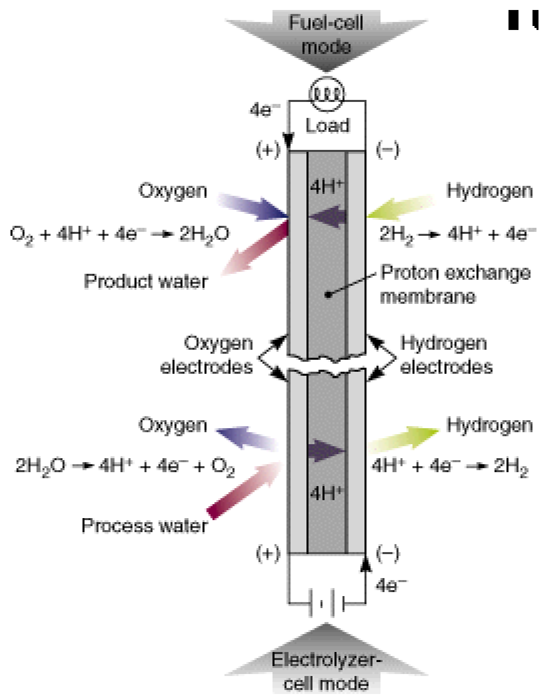


Figure 4 – Unitized Regenerative Fuel Cell [9]

PEM Fuel Cells have been used since 1960s for Gemini and Apollo spacecraft for on-board power supply [10]. LLNL physicist F. Mitlitsky , B. Myers, et al. (1999) developed a 50 watt single proton exchange membrane cell modified to reversibly operate as an Electrolyzer. LLNL adopted PEM static feed reversible (unitized) fuel cells (URFCs) and were demonstrated over 700 cycles at 2 MPa [11] for small satellite energy storage. A schematic diagram of the URFC is shown in figure 4.

When the URFC is operated in the Fuel Cell mode, oxygen and hydrogen gases are supplied which combine to form water and releases a direct current through the electrodes. Whereas, when it operates as an Electrolyzer, distilled water is supplied as an input and a direct current is passed through the electrodes, which break the water molecule into hydrogen and oxygen gases. These gases are collected from the electrodes and later on combusted to generate thrust.

2.3 CubeSat – scale Electrolysis Propulsion System

Advances in other areas of satellite development have made it possible to conceive of missions involving CubeSats outside of Low Earth Orbit (LEO).[12] A water electrolysis propulsion system[3] for 3U CubeSats was proposed by Peck and Zeledon (2011) that could be available as a viable propulsion systems at this scale. The system described here is based on a 3U CubeSat that spins about its axis of inertia during orbit raising. The system overview is given in the Figure 5. The water tanks (A) store propellant and generate Hydrogen and Oxygen through electrolysis using power from solar cells (B). The gases are combusted in the chamber (C) and expanded through a nozzle (D) to generate thrust. The mode of operation for the satellite is to electrolyse water while it is in sunlight and then produce thrust after combustion only once per orbit to ensure sufficient gas has accumulated for a successful burn.

Cornell's CubeSat design required solar panels are located on all faces of the 3U CubeSat with at least 30% efficient in converting solar energy into electrical energy.

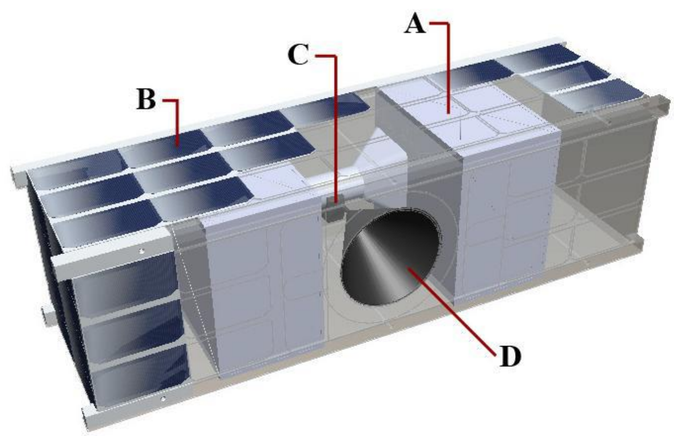


Figure 5 - Electrolysis Propulsion for 3U CubeSat [3]

The Electrolyzers are composed of two electrodes (cathode and anode), both made of nickel mesh strips. They are placed inside a liquid water tank, which also contains potassium hydroxide (KOH) as an electrolyte. The nickel strips are separated by a thin layer of non-conductive mesh which ensures the passage of ions between the electrodes. The conductive mesh prevents the passage of water or electrolyte though it but allows the ions to pass through it thereby completing the circuit. Several electrode pairs are placed in parallel to ensure peak power for electrolysis of water. Cornell University conducted various experiments to determine efficiency of the nickel electrodes as Electrolyzers. It was found that for an Electrolyzer using an alkaline solution, the efficiency of the nickel electrodes is proportional to the concentration of KOH in the electrolyte solution. Figure 3 shows the results of their experiment compared to a PEM electrolyzer.

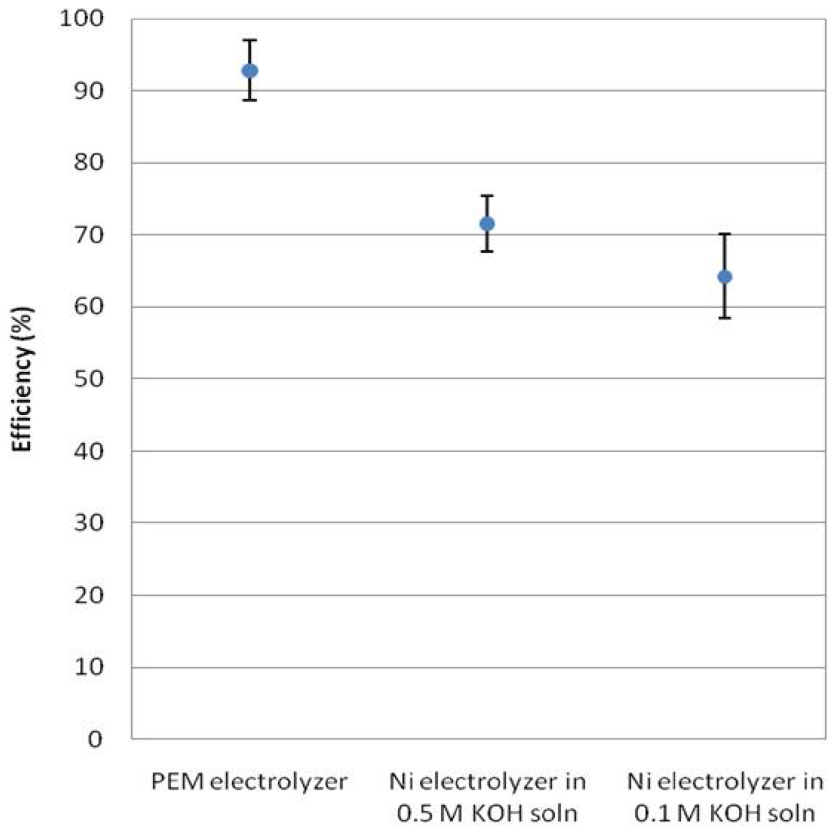


Figure 6 – Efficiency of Electrolyzers [3]

From the above given figure, efficiency of this model of PEM electrolyzer in converting electrical energy into chemical energy of the electrolyzed gases has been measured to be 85% -90% range. This experiment led to a change in the design of the prototype made by Cornell University. They have replaced the Ni Electrolyzer with a commercially available PEM electrolyzer. Since PEM electrolyzers do not require dissolved electrolytes in the water, distilled water is used as a propellant in the propulsion system [13].

The electrolysis propulsion system occupies most of the volume up to 2U and leaves about 1U of the space for payload and other components. 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 [13]. Separation of electrolyzed gases from the liquid water is achieved by constant spin of the spacecraft. A centrifugal force generate by constant spin of the CubeSat exerts greater force on water by pushing it towards the end of the chamber, thereby separating it from the 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 approximate impulse of 0.6Ns per pulse [14]. The spin in the spacecraft is established after separation from the mother vehicle by magnetic torquers [15] embedded in the solar panels. The spin state of the spacecraft before separation is prevented by the nature of the P-POD deployer[16] which latches on to the CubeSat until launch. Figure 7 shows the CubeSat rotation and the concept of separation of gases from the liquid water.

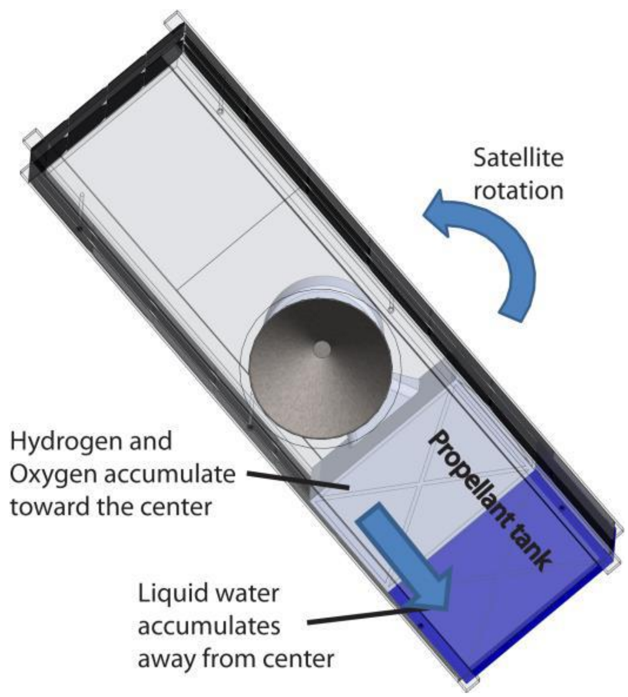


Figure 7 – CubeSat Rotation and Gas Separation [14]

Since the spacecraft makes use of the magnetic field of Earth for generating spin about its thrust axis, this design is not going to work outside the earth's gravity well. Hence, the concept is only limited to missions up to Geostationary Earth Orbit (GEO) orbits. In order to make CubeSat mission possible beyond this, an alternative solution is required.

2.4 Other Propulsion Systems for CubeSats

2.4.1 Hydro-s Thruster

Tethers Unlimited, Inc (TUI) has developed a CubeSat Water Electrolysis Propulsion System named Hydros that they claim provides orbit aglitiy, precision pointing, and rapid maneuvering to CubeSats and other small satellites. [17] This system is also powered by water which is electrolyzed into hydrogen and oxygen on-orbit to deliver 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 0.8N of thrust at 300s 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. The proposed 0.5U and 1U designs are shown in Figure 8.

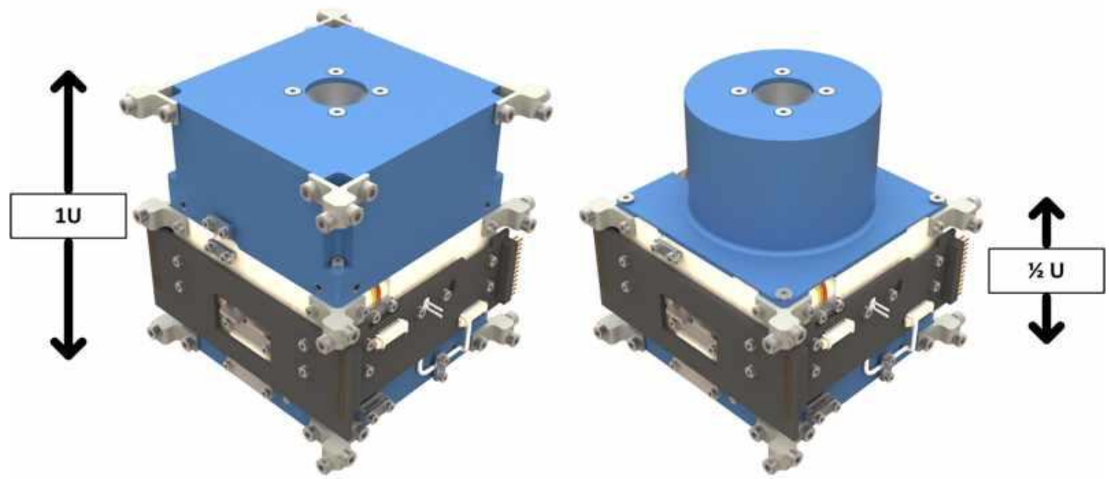


Figure 8 – Hydros 0.5U and 1U Configuration [17]

TUI has not published detailed specifications addressing critical questions such as the type of Electrolyzer used; separation of electrolyzed gases from water; redundancy of the proposed system.

2.4.2 Busek Space Propulsion and Systems

Busek Co. Inc. has developed several types of thruster systems for CubeSat and other small spacecraft missions, including electrospray thrusters, micro-resistojet, pulsed plasma thrusters, RF ion thruster and a green monopropellant thruster (see Figure 9). Most of these systems produce a thrust on the order of milli-newtons. The applications of these thrusters range from attitude control to large delta-V maneuvers up to 400 m/s.

Although most of these systems would fit in less than 1U volume, they cannot possible be used in missions involving orbit raising or interplanetary trajectories for larger CubeSats (6U). Many other corporations make similar kind of thrusters for CubeSats, but none of them are sufficient for orbit raising or for missions which would require ΔV of more than 1000m/s.

Figure 9 – Busek Co. Inc. CubeSat Thrusters [18]

CHAPTER 3

METHODOLOGY

3.1 Photovoltaic Electrolysis Propulsion System

3.1.1 Electrolysis of Water

Molecular bonds act like a potential energy well. When sufficient energy is provided, these bonds can be broken. This principle is used in the electrolysis of water to produce Hydrogen and Oxygen. It was discovered by two Dutchmen, Paets van Troostwik and Deiman in the year 1789. [19] When electricity is introduced electrodes in water, Hydrogen and Oxygen ions are attracted to the opposite charged electrode. Hydrogen ions are collected on the cathode (negatively charged electrode) and Oxygen will collect on the anode (positively charged electrode). This technique is broadly used to make hydrogen fuel.

The efficiency of the system depends on various aspects including the conductivity of water. Although pure water is a good conductor of electricity, the efficiency improves by use of other electrolytes such as salt water. This has no effect on the rate of dissociation, but rather on the rate of ion transport toward the electrodes.

3.1.2 Hydrogen Gas as Propellant

Hydrogen gas is often advocated as an energy medium because it is an energy storage solution and a promising fuel. Since significant quantities of Hydrogen are not available in nature in pure form, it has to be produced. Currently, the main method of hydrogen production is by steam methane reforming. This process uses an external source of hot gas to heat tubes in which a catalytic reaction takes place that converts hydrocarbons such as methane into hydrogen and carbon monoxide. The shortage of methane has translated into continuous climb in price which is currently 10%-30% higher than last year. Once, the cost of methane increases due to scarcity, electrolysis of water is a viable option for hydrogen production.

Hydrogen when combined with oxygen produces water. This is an exothermic reaction meaning that energy is given off. Spacecrafts, and possibly motor vehicles, in the near future, can make use of this energy for propulsion purposes. When hydrogen and oxygen are combined in the presence of a spark, they combust to produce hot gases in the form of water vapor which can be expanded using a nozzle to produce thrust. Although the thrust produced may be low, it is sufficient to propel a CubeSat in space.

3.1.3 PEM electrolyzer

There are two types mainstream, well proven of electrolyzers: (i) alkaline and (ii) Proton Exchange Membrane (PEM). PEM electrolyzers are reversible devices for hydrogen systems which are more popularly known as PEM Fuel Cells. PEM based electrolysis has many advantages when compared to conventional alkaline based electrolysis, e.g., it requires less space, mass and power, and has an intrinsic ability to cope with transient electrical power variations, generates gases with a high degree of purity, and has the potential to compress hydrogen at a higher pressure within the unit and with a higher safety level. PEM based electrolysis is historically linked with DuPont’s Nufon [20] membrane. Figure 10 shows the schematic diagram of a PEM electrolyzer.

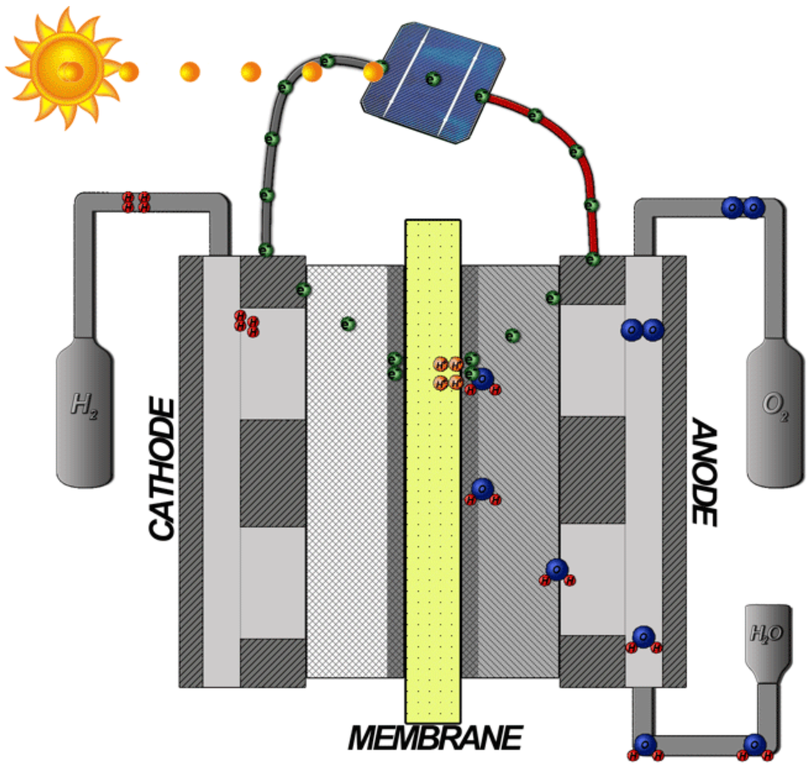


Figure 10 – Schematic Diagram of PEM electrolyzer [21]

The PEM electrolyzer consists of a proton exchange membrane which restricts the flow of electrolyte between the electrodes. But it does allow for the flow of ions through it. When a direct current is applied to the electrodes, water breaks down into hydrogen and oxygen ions which are collected at the electrodes.

3.2 System Overview

Electrolysis propulsion is the collective name for an integrated set of technologies that offer new options for CubeSat propulsion. Water will be used as a propellant for the system. Since, it is environment friendly, it shall be referred to as Green propellant in the discussion hereafter. The green propellant, stored on the spacecraft, is electrolyzed to generate and separate gaseous hydrogen and oxygen. These gases, stored in lightweight pressure tanks, can be combusted, as discussed above, to generate thrust. A CubeSat using Electrolysis propulsion can be totally inert and non-hazardous during assembly and launch. The capability for high I_{sp} propulsion and the low mass overhead required to store unpressurised water can take secondary payloads through large total ∇V missions.

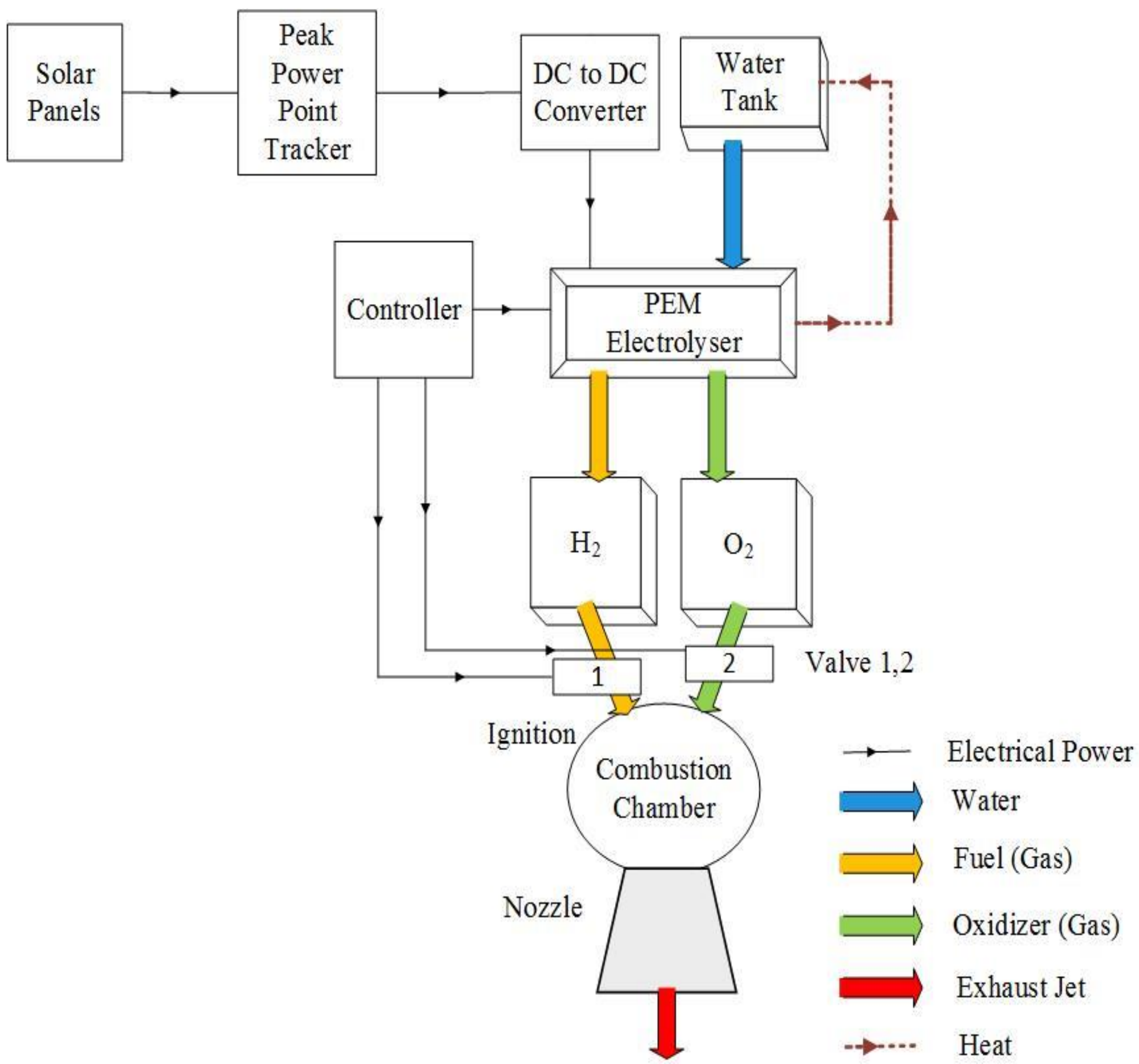


Figure 11 – Schematic Diagram of the Proposed System

In this system, it is assumed that the energy required for electrolysis to produce thrust for the CubeSat comes from the solar cells. Electrolysis of water is achieved by the use of a PEM electrolyzer. Several of these electrolyzer units are placed in series so that maximum hydrogen can be produced from electrolysis of water.

Spacecraft rotation (controlled by a reaction wheel centered on the maximum axis of inertia) frees the gas bubbles from the electrolyzer. The centrifugal force from the space craft spin ensures that water goes through to the inlet of the Electrolyzer. When there is sufficiently high pressure and a burn is desired, hydrogen and oxygen are allowed to flow into the combustion chamber where the mixture is ignited. The hot gaseous mixture expands through a small nozzle and is expelled to provide an impulse. The process may be repeated as frequently as allowed by the rate of hydrogen production.

The Photovoltaic Electrolysis Propulsion System works by converting the solar energy captured from the sun into chemical potential energy, which in turn, is freed through combustion, generating thrust. In this process, the first step is to convert solar energy from the sun into electrical energy using photovoltaic cells on the solar panels. This electrical energy is used to electrolyze liquid water into gaseous hydrogen and oxygen.

The process described here is based on a 6U CubeSat that spins about its maximum axis of inertia during orbit raising. This provides passive attitude stability and manages the effect caused by thrust induced torque. Any mechanical misalignment is also minimized by this spin. This kinematics provides a spin field which causes the electrolyzed gases to collect at the center of the propellant tank due to the centrifugal force. The collected gases can be passed into a combustion chamber when the required pressure is achieved. The onboard computer then commands the igniter to produce a spark, combusting the hydrogen and oxygen mixture, which expands through a small nozzle located approximately on the spin axis and generates thrust.

3.3 System Concept

A concept of the proposed system was developed bearing in mind all the restrictions enforced on CubeSat design specification and mission requirements, as well as the resources available at the university level. The final specifications assumed a 6U model of a CubeSat which would have a total mass of 14kg and a dry mass of 4.5kg, with a 6U volume dedicated to propulsion and the entire structure surrounded by solar panels around its surface.

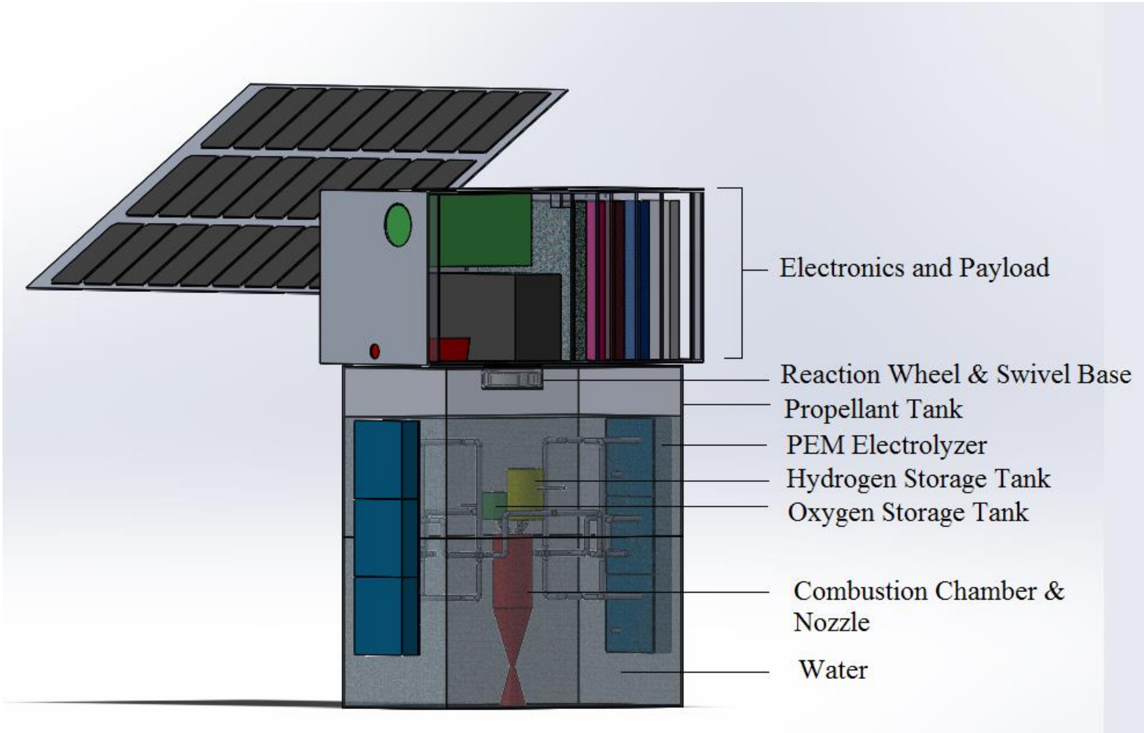


Figure 12 – CAD Model of Proposed System Concept

The propulsion section 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. Figure 12 shows the CAD model of the proposed system. The individual parts of the system are explained briefly below.

3.3.1 Propellant Tank

The propellant tank constitutes the entire volume available from the 6U part of the model assigned for propulsion. 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.

3.3.2 PEM electrolyzer

Each PEM electrolyzer measures 5.4×5.4×1.7 cm and weighs 65g. Figure 13 shows the model of the Horizon PEM electrolyzer used in the experiment. A total of 6 units are located strategically inside the propellant tank. They are divided into 2 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 of the CAD model. These electrolyzers are remade of metal and then used for spacecraft application.

Figure 13 – Horizon PEM electrolyzer [22]

3.3.3 Storage Tank

Hydrogen and Oxygen are stored separately to increase the safety of the system by preventing premature combustion in 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:

$$\sigma_\theta = \frac{Pr}{t} \quad (1)$$

Where,

σ_θ	=	Hoop Stress
P	=	Internal Pressure
r	=	Mean radius of the cylinder
t	=	Wall Thickness

Assuming the value of the storage pressure at 6bar, the value of minimum thickness is 0.19mm. Since this is very small, it was assumed to keep the thickness of the wall to 1mm for the purpose of easy machining. Both the storage tanks are 2.5 cm in diameter. The hydrogen tank is 3 cm long and the oxygen tank is half as along since the electrolyzed gases are produced in a ratio of 2:1. The outlets from all the electrolyzers are connected to the inlet of the respective storage tanks through pipelines.

3.3.4 Thrust Chamber

The thrust chamber is also made of Aluminum 6061-T6 with a thickness of 1mm to ease the purpose of machining yet again as the minimum thickness required to prevent the tank from a rupture is much less. 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.

3.3.5 Swivel Base and Reaction Wheel

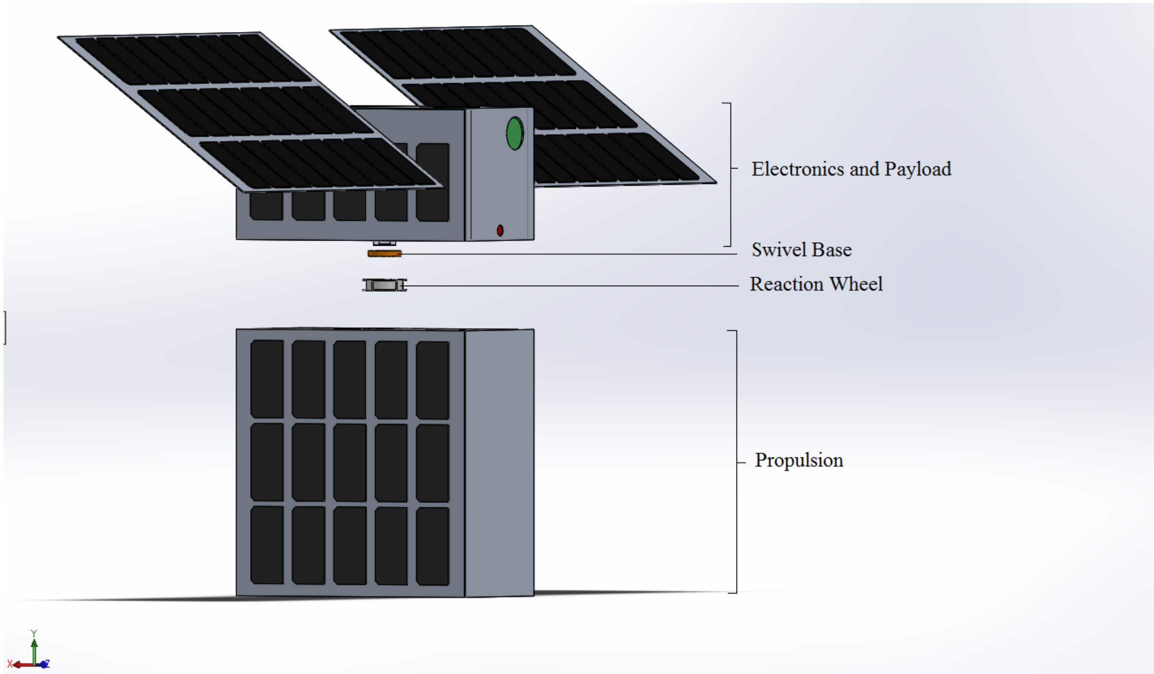


Figure 14 – Exploded View of Reaction Wheel and Swivel Base

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. The exploded view of the same can be seen in figure 14. It was chosen to use the Blue Canyon Tech's [23] micro reaction wheel for this purpose which operates at 1.7W. This can be seen on Figure 15.

Figure 15 – Blue Canyon Tech's Micro Reaction Wheel [23]

3.4 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 drag power from the battery and rotate the propulsion system at a rate of 2rad/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.

Then, the propellant, which is a solution of water and other additives, 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 gases 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. A graphical representation of the CubeSat spin is shown in figure 16.

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.

3.4.1 Freezing Point Depression

The freezing point of water can be depressed by adding a solvent such as salt. It is known that the use of table salt (NaCl) on icy roads helps to melt ice from the roads by reducing the freezing point of ice. The freezing point depression ΔT_f 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 [24]. Here, K_f is the Freezing Point Depression Constant.

$$\Delta T_f = K_f c_m \quad (2)$$

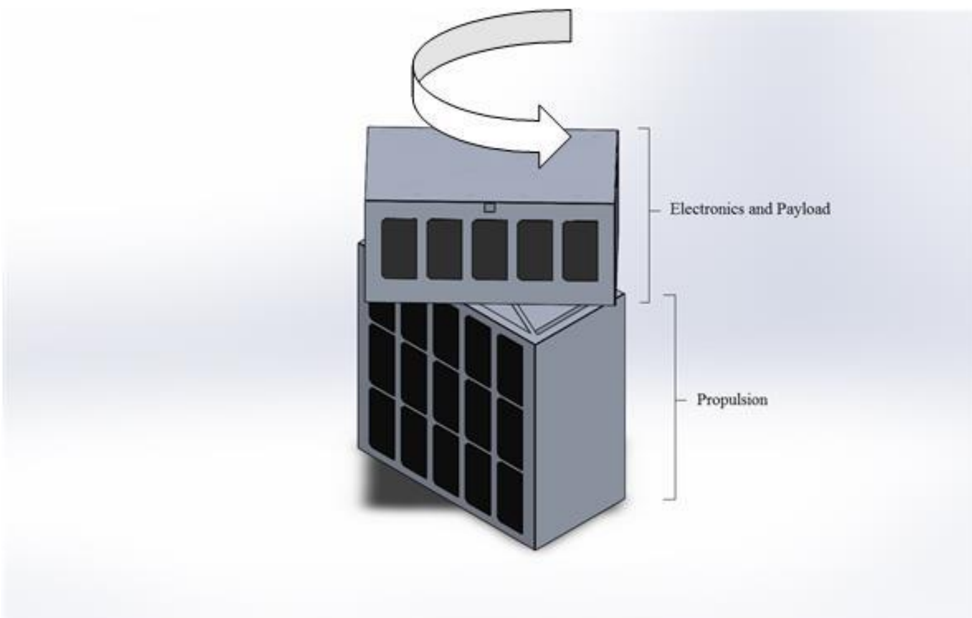


Figure 16 – Propulsion Tank Spins along the Axis of Thrust While Electronics and Payload Remain Fixed

A study conducted by Meewisse J.W and Ferreira C.A (2001) which followed that lithium chloride, sodium chloride and potassium formate are advantageous freezing point depressants comes in handy. [25] Hence, for the purpose of all experiments conducted it was decided to use sodium chloride and lithium chloride which are easily available and safe to handle.

Experiments were conducted in order to determine an acceptable solution which yielded a sufficient point depression relative to distilled water. Initially, a 10% sodium chloride solution was made using 100 ml of water. This was stored at -5°C for a duration of 3 hours in a freezer alongside distilled water. It was observed that the distilled water froze but the salt solution was still in liquid state. When the temperature was decreased to -10°C, it was observed that the 10% salt solution also froze after a duration of 3 hours. Later when the concentration of the salt solution was increased to 20%, it was observed that at -10°C the solution remained in liquid state.

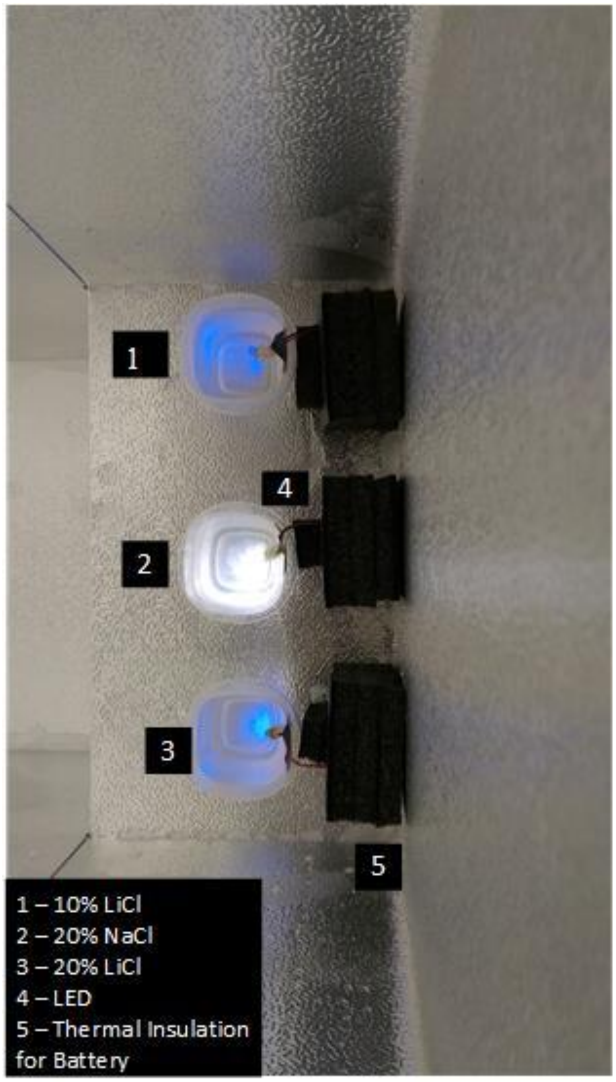


Figure 17 – Salt Solutions inside Chest Freezer

When the same experiment was performed by a 10% Lithium Chloride solution, the solution remained in a liquid state even at -10°C. Although, when these solutions were stored for over a period of 24 hours, it was observed that the salt in the solution had settled out and caused the water to freeze. In order to avoid this, an LED light was dipped inside the solution. The motive behind this was to induce circulation of the water through convective current caused by the heat produced by the LED. The battery for the LED was thermally sealed and placed inside the freezer beside the water solution. An observation was made with this arrangement over 24 hours, 48 hours, and 96 hours. The salt solutions were still in liquid state. Although this is not an issue that will be of concern during the operation of the CubeSat, it is definitely a solution for the propellant storage before launch. Figure 16 shows a representation of the conducted experiment.

3.5 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 delta V [26]. The characteristics of a successful propulsion system at a CubeSat scale are: [3]

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.

3.5.1 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 350s – 390s [2]. For a control volume of a thrust chamber, the steady flow energy equation can be given as:

$$\frac{\dot{Q} - \dot{W}_e}{\dot{m}} = \left(h_e + \frac{V_j^{\,2}}{2} + gz_e\right) - \left(h_c + \frac{V_c^{\,2}}{2} + gz_c\right) \quad (3)$$

Where,

$\dot{m}$	=	mass flow rate through the nozzle
h_c	=	enthalpy of the gas in the chamber
h_e	=	enthalpy of the gas at the exit of nozzle

Since the nozzle is of fixed construction, the rate at which is does 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 3 for the control volume therefore becomes:

$$\frac{{V_j}^2}{2} = h_c - he \quad (4)$$

In Photovoltaic Electrolysis Propulsion System (PVEPS), we use hydrogen as the fuel and oxygen as 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 = 4725.8214 m/s. This means the maximum possible I_{sp} from the system is 482.22s. 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 0.45s, it can be around 75% to 88%. [27] This means the specific impulse available for the given system is between 361.66s and 424.35s.

At this efficiency, using the Tsiolkovsky rocket equation, the ΔV produced by the system for a 14kg spacecraft with 9.5 kg propellant is around 4022 m/s.

$$\Delta V = V_j \times \ln\frac{1}{R_m} \quad (5)$$

Where,

ΔV = Velocity budget available for a mission

V_j = Exhaust velocity of the hot gas

R_m = Mass Ratio of the spacecraft

From	**To**	**Required ΔV**
LEO	LLO(Low Lunar Orbit)	4040 m/s
LEO	EML -1(Earth Moon Lagrange 1)	3770 m/s
LEO	EML -2(Earth Moon Lagrange 2)	3430 m/s

Table 1 - ΔV Requirement for Various Missions Extracted from STK

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.[28] This gives ample scope to enable the spacecraft onto a lunar transfer orbit by exploiting the weak stability boundary in the Earth-Moon system. Table 1 gives the ball park values of ΔV required from Low Earth Orbit to Lunar Orbit or the Earth Moon LaGrange points.

3.5.2 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 expand 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:

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

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

Where,

P_t	=	Pressure at nozzle throat
P_c	=	Pressure inside combustion chamber
k	=	Specific Heat Ratio
T_t	=	Temperature at nozzle throat
T_c	=	Temperature inside combustion chamber

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

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

Where,

q	=	Propellant mass flow rate
R	=	Universal Gas Constant
M	=	Molecular mass of Water Vapor

Using this data, the combustion chamber can be designed. Considering a mass flow rate of 1g/s, as expected for the electrolyzed propellant for one pulse, the nozzle throat diameter is calculate to be D_m = 78mm. The convergent cone half angle of the convergent cone section has a half angle between 12 to 18 degrees. The divergent half angle is almost a standard of 15 degree as it is a compromise on the basis of weight, length and performance. [29] The calculated values are summarized in 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

Table 2 – Nozzle Design Analysis

3.5.3 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^*[25] 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:

$$L^* = \frac{V_c}{A_t} \quad (8)$$

$$V_c = A_1 L_1 + A_1 L_c (1 + \sqrt{A_t/A_1} + A_t/A_1) \quad (9)$$

Where,

V_c = Volume of Combustion Chamber

L_1 = Length of the cylinder

L_c = Length of conical frustum

A_1 = Area of cylindrical chamber

The value of L^* is chosen from available databases for propellant combination. [25] The volume of the combustion chamber is computed to be is $V_c = 5 \times 10^{-5}$ m^3. The calculated values are shown in table 3.

Combustion Chamber Design	
Combustion Temperature (K)	1300
Mass of Gaseous Mixture (g)	1
Chamber Pressure ($N/^{m2}$)	6×10^{5}
Volume of Chamber (kg/m^3)	4.5×10^{-5}
Diameter of Cylindrical Chamber (m)	0.025
Area of Cylindrical Chamber (m^2)	4.9×10^{-4}
Length of Cylindrical Chamber (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}
Length of Converging Cone Frustum (m)	0.041

Table 3 – Combustion Chamber Design Analysis

3.6 Experimental Procedure

A list of experiments was conducted to justify the use of salt solution as an electrolyte for the process of electrolysis using a PEM electrolyzer. These experiments were also conducted at different temperatures to check the efficiency of the PEM electrolyzer for various operating conditions. 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.

3.6.1 Experiment 1 – Distilled Water as Electrolyte

Aim: To gather hydrogen production rate through electrolysis of distilled water using a PEM electrolyzer at standard temperature and pressure

Apparatus:

- Horizon PEM electrolyzer
- Graduated Cylinder (2Liter) – 2
- Tray (8 liters)
- DC Power Supply
- Thermometer
- Water (6 liters)
- Burrete Stand and Clamps
- Syringe
- Check Valve

- Silicon Tubing
- Timer

Experiment Setup: The tray is filled with 2 liters of 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. This experimental setup has been shown in figure 18.

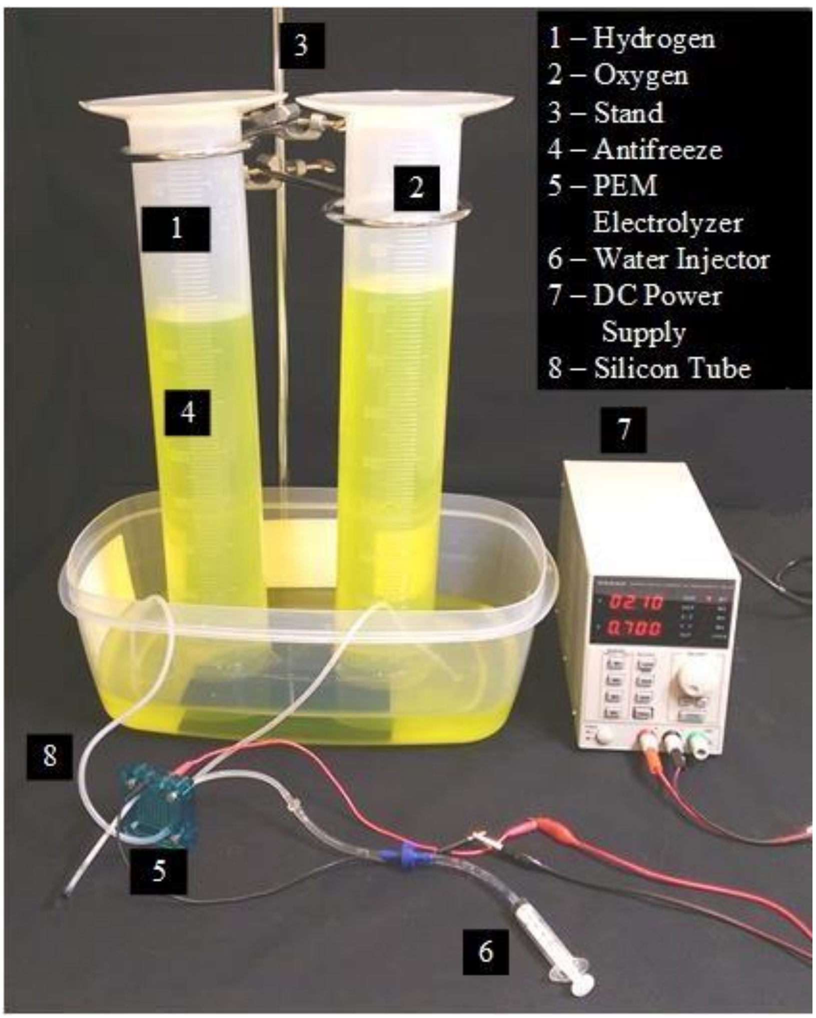


Figure 18 – Experimental Setup

Procedure: 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 2V. Once the Electrolyzer is connected to the DC power supply, bubbles can be seen collecting on both graduated cylinders. This shows that the setup is working.

The DC power supply is now set to 1.4 V. The Electrolyzer is connected to the power supply over a period of five minutes. At the end of five minutes, readings of the water level in the graduated cylinders are noted separately. A reading of the temperature is also noted at this point. The value of current supplied from DC power supply is also tabulated.

More water is forced into the Electrolyzer using the syringe. The syringe can be refilled at any point of time since the check valve restricts the flow of fluid in only one direction. The voltage input is now increased from 1.4 to 1.5V and another set of readings are tabulated. This process is repeated until the voltage reading is 3.1 V and corresponding readings are tabulated. Once the experiment is complete, the Electrolyzer has to be placed in a closed container. The Hydrogen and Oxygen gases that were collected in the graduated cylinder are safely discarded.

3.6.2 Experiment 2 – 20% NaCl as Electrolyte at 25°C

Aim: To gather hydrogen production rate through electrolysis of 20% NaCl solution using a PEM electrolyzer at standard temperature and pressure

Apparatus:

- Horizon PEM electrolyzer
- Graduated Cylinder (2Liter) – 2 No.
- Tray (8 liters)
- DC Power Supply
- Thermometer
- Water (6 liters)
- Sodium Chloride, ACS+ Grade
- Burrete Stand and Clamps
- Syringe
- Check Valve
- Silicon Tubing
- Timer

Experimental Setup: A 20% salt solution is made by dissolving 25g of sodium chloride into 100ml of water. The mixture is constantly stirred over 5-10 minutes to form a solution. The formula is to make a solution by weight percentage is as follows:

$$x = \frac{p \times y}{1 - p} \qquad (10)$$

Where,

x	=	Weight of solute (g)
p	=	Weight Percent of solution
y	=	Volume of solvent (ml)

Procedure: The experiment is setup and executed in the same manner as the previous, however using the sodium chloride solution in place of water.

3.6.3 Experiment 3 – 20% NaCl as Electrolyte at -5°C

Aim: To gather hydrogen production rate through electrolysis of 20% NaCl solution at -5°C using a PEM electrolyzer.

Apparatus:

- Horizon PEM electrolyzer
- Graduated Cylinder (2Liter) – 2 No.
- Tray (8 liters)
- DC Power Supply
- Thermometer
- Water (6 liters)
- Sodium Chloride, ACS+ Grade
- Burrete Stand and Clamps
- Syringe
- Check Valve
- Silicon Tubing
- Timer
- Chest Freezer

Procedure: The experiment is setup and executed in the same manner as the previous, however using the sodium chloride solution in place of water. The sodium chloride solution is stored in a chest freezer at -5°C. It is collected in a syringe and injected into the electrolyzer before every iteration in order to maintain the temperature of the salt solution throughout the experiment. This experiment is then repeated for the same salt solution at -10°C.

3.6.4 10% Lithium chloride solution As Electrolyte

The above mentioned experiments are performed for 10% Lithium Chloride solution as electrolyte at 25°C, -5°C and -10°C. The results are tabulated, plotted and discussed in the next chapter.

3.6.5 20% Lithium Chloride solution as Electrolyte

An experiment was performed with 20% Lithium chloride solution as electrolyte at 25°C. Though it was not necessary to evaluate a 20% lithium chloride solution at -5°C and -10°C, it was decided to do so in order to have a better understanding of the results produced from a sodium chloride solution of the same concentration. The result is tabulated and plotted in the next chapter.

CHPATER 4

RESULTS AND DISCUSSION

4.1 PEM Electrolyzer Efficiency

Results of the experiments detailed in the previous chapter were tabulated and graphs of the same were plotted to analyze the collected data. Using this data analysis, the maximum rate of hydrogen production and efficiency of the PEM electrolyzer for different electrolyte solutions and operating conditions was determined. While conducting these experiments, an average of two readings was used for tabulating and calculations. After each experiment was completed, extreme caution was exercised to get rid of the electrolyzed gases separately.

4.1.1 Distilled Water at Standard Room Temperature and Pressure

As discussed in the previous chapter, an experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at standard pressure and temperature when the electrolyte used was distilled water. The values of Voltage, Current and Hydrogen production rate were tabulated as shown in Table 4.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0	300	0
1.5	0.02	300	0
1.6	0.11	300	1.8
1.7	0.20	300	1.6
1.8	0.24	300	2.4
1.9	0.51	300	2
2.0	0.62	300	6.4
2.1	0.69	300	5.8
2.2	0.69	300	5.6
2.3	0.78	300	5.8
2.4	0.65	300	7
2.5	0.34	300	4
2.6	0.34	300	3.2
2.7	0.34	300	3
2.8	0.33	300	2.6
2.9	0.37	300	3.6
3.0	0.3	300	3.6
3.1	0.40	300	3.6

Table 4 – Distilled Water Electrolyte Experiment at STP

The results from the experiment show that for the given electrolyzer, there is no current for an input voltage of 1.4V. When the voltage was increased to 1.5V there was a noticeable current in the circuit but no hydrogen production over duration of 5 min. But, when the voltage was increased to 1.6V, there was a flow of current and also noticeable hydrogen production over 5 min duration. The value of current increased up to 2.3V after which there was drop of current up to 3.1V where the experiment was stopped since the given Electrolyzer was rated only to 3V. From this data, the Hydrogen Production Rate and current were plotted with respect to Voltage in figure 19 and 20 respectively.

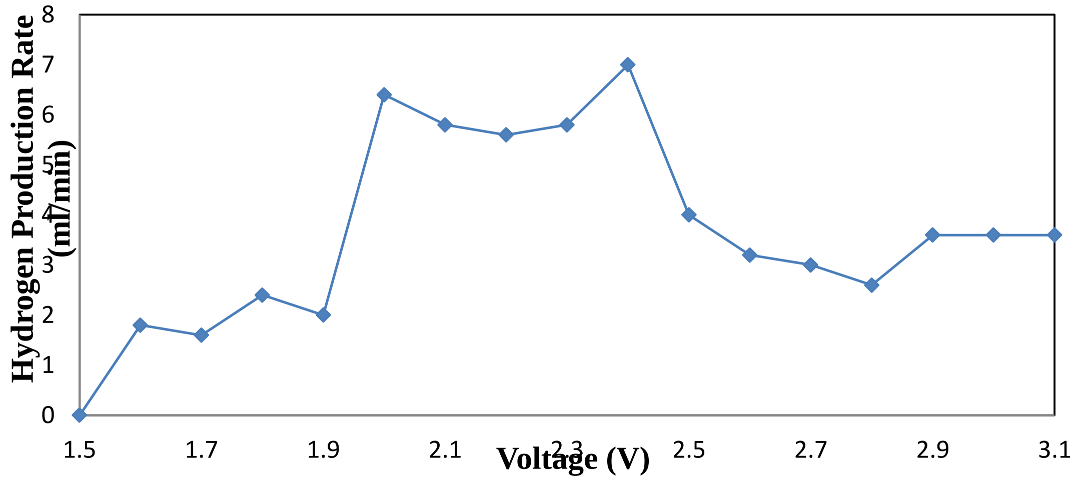


Figure 19 – Hydrogen Production Rate vs Voltage for Distilled Water as Electrolyte at STP; Experiment Standard Deviation – 5%

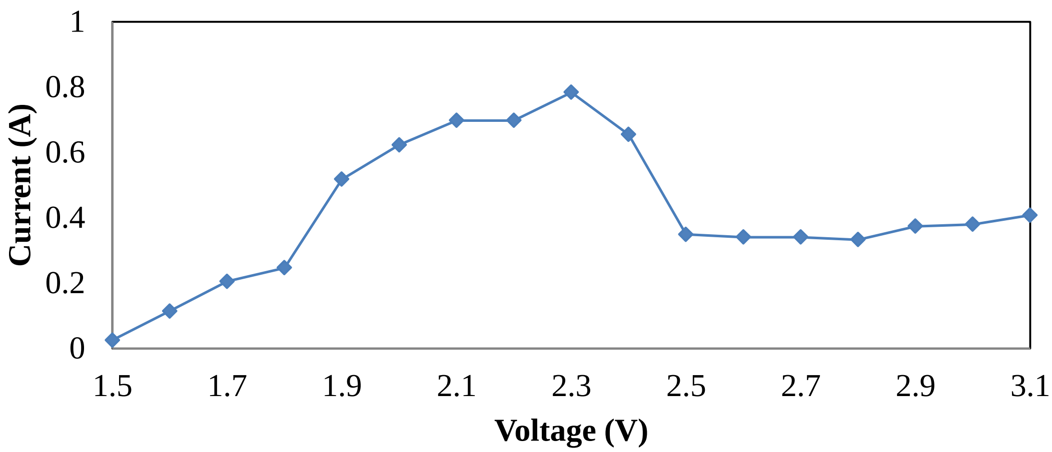


Figure 20 – Current vs Voltage for Distilled Water as Electrolyte at STP; Experiment Standard Deviation – 5%

For distilled water as an electrolyte at STP, the peak power value was 1.80W and the rated power was 1.57W.

4.1.2 NaCl (20% Solution) at Standard Room Temperature and Pressure

As discussed in the earlier chapter, the experiment was repeated using a 20% solution of sodium chloride (ACS grade) as the electrolyte. The resulting data are tabulated in Table 5.

The results from the experiment show that for the given electrolyzer, there is a very meager amount of current for an input voltage of 1.5V. The value of current increased linearly with voltage, up to a value of 2.2V. The value of current decreased from 2.3V up to 3.1V where the experiment was stopped since the given Electrolyzer was rated only to 3V. Graphs of hydrogen production rate vs voltage, current vs voltage, and hydrogen production rate vs power input are plotted in Figure 21and 22, respectively.

It was observed that the maximum rate of hydrogen production was reduced to 6.2 ml/min when the electrolyte used was 20% sodium chloride solution.

Voltage (V)	**Current (A)**	**Time (s)**	**Hydrogen Production Rate (ml/min)**
1.5	0.02	300	0.4
1.6	0.11	300	0.6
1.7	0.20	300	0.8
1.8	0.31	300	2.6
1.9	0.42	300	3.6
2.0	0.52	300	4.2
2.1	0.63	300	4.6
2.2	0.69	300	5
2.3	0.65	300	6.2
2.4	0.40	300	4.8
2.5	0.20	300	2.6
2.6	0.19	300	1.4
2.7	0.2	300	1.8
2.8	0.22	300	2
2.9	0.24	300	1.6
3.0	0.21	300	2.4
3.1	0.25	300	2.2

Table 5 –20% Sodium chloride solution as Electrolyte Experiment at STP

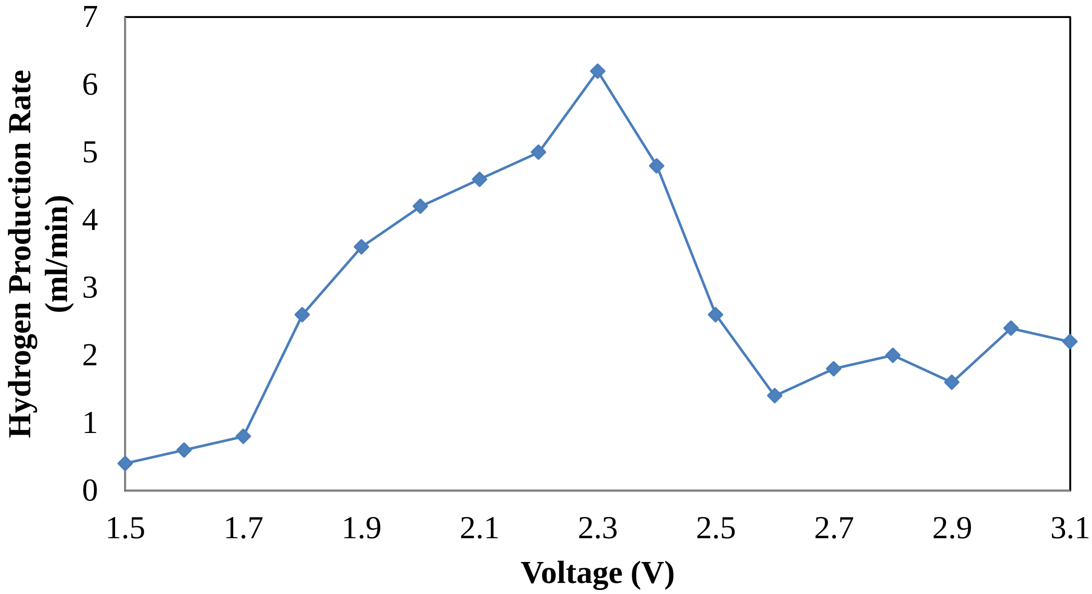


Figure 21- Hydrogen production rate vs voltage for 20% Sodium Chloride solution Electrolyte at STP; Experiment Standard Deviation – 7%

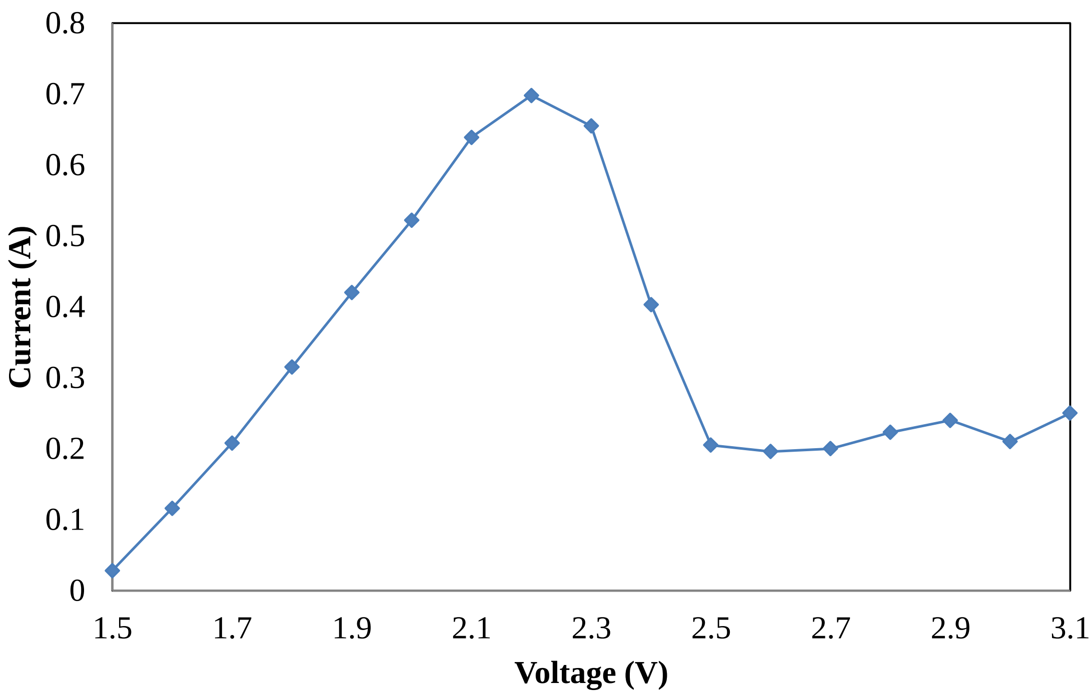


Figure 22 – Current vs voltage for 20% Sodium Chloride solution as Electrolyte at STP; Experiment Standard Deviation – 7%

For 20% Sodium chloride solution as an electrolyte at STP, the peak power value was 1.53W and the rated power was 1.50W.

4.1.3 NaCl (20% Solution) at -5°C

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of the electrolyzer at -5°C when the electrolyte used was 20% solution of sodium chloride (ACS grade). The data is again tabulated as shown in Table 6.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0	300	0
1.5	0.01	300	0.2
1.6	0.07	300	0.4
1.7	0.11	300	0.4
1.8	0.12	300	1.2
1.9	0.11	300	1.4
2.0	0.11	300	0.6
2.1	0.10	300	0.2
2.2	0.11	300	0.2
2.3	0.11	300	1.4
2.4	0.13	300	1.8
2.5	0.16	300	0.4
2.6	0.20	300	1.6
2.7	0.26	300	2.4
2.8	0.33	300	2.4
2.9	0.39	300	2.4
3.0	0.47	300	3.6
3.1	0.53	300	4.0

Table 6 –20% Sodium chloride solution at -5°C as electrolyte experiment at -5°C

The results from the experiment show that for the given Horizon PEM electrolyzer, there is no current for an input voltage of 1.4V. When the voltage was increased to 1.5V there was a noticeable current in the circuit and a very meagre rate of hydrogen production over duration of 5 min. The value of current remains small till the input voltage was 2.5V. But when the voltage was increased to 2.6V, there was an increase in the value of current and also noticeable hydrogen production over 5 min duration. The value of current increased up to 3.1V, where the experiment was stopped since the given Electrolyzer was rated only to 3V. A graph of voltage vs current, hydrogen production rate vs voltage power and hydrogen production rate vs power input were plotted. It was observed that maximum rate of hydrogen production reduced to 4 ml/min when the electrolyte used was 20% sodium chloride solution at -5°C compared to the salt solution at standard room temperature and pressure.

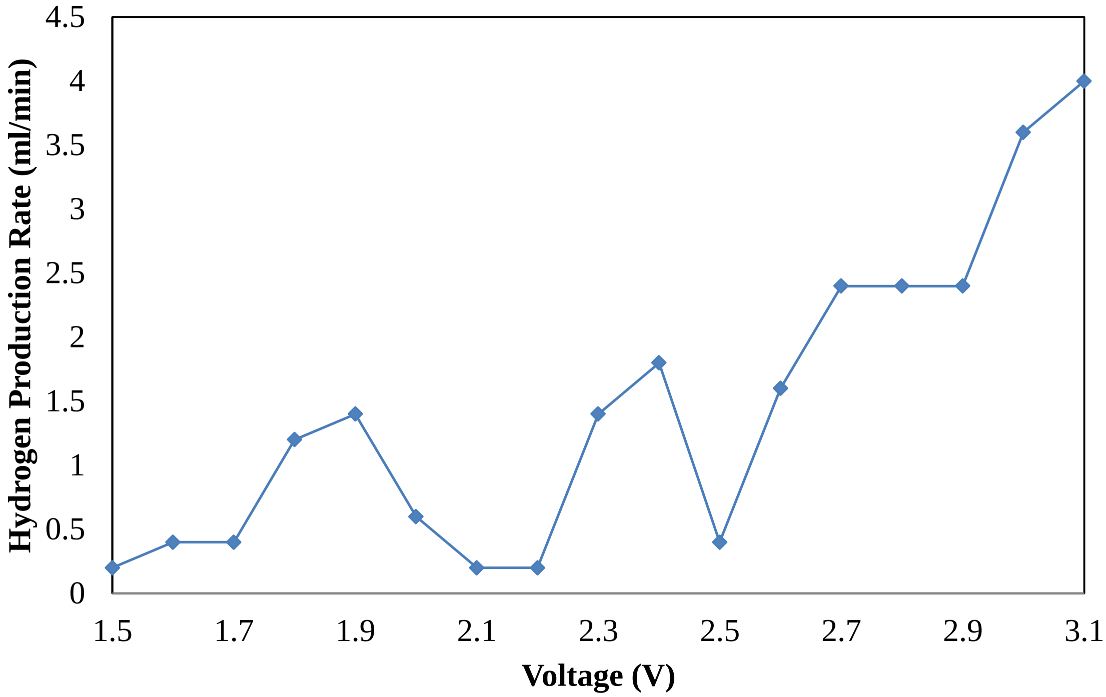


Figure 23 - Hydrogen Production Rate vs Voltage for 20% Sodium Chloride solution at -5°C Electrolyte; Experiment Standard Deviation – 7%

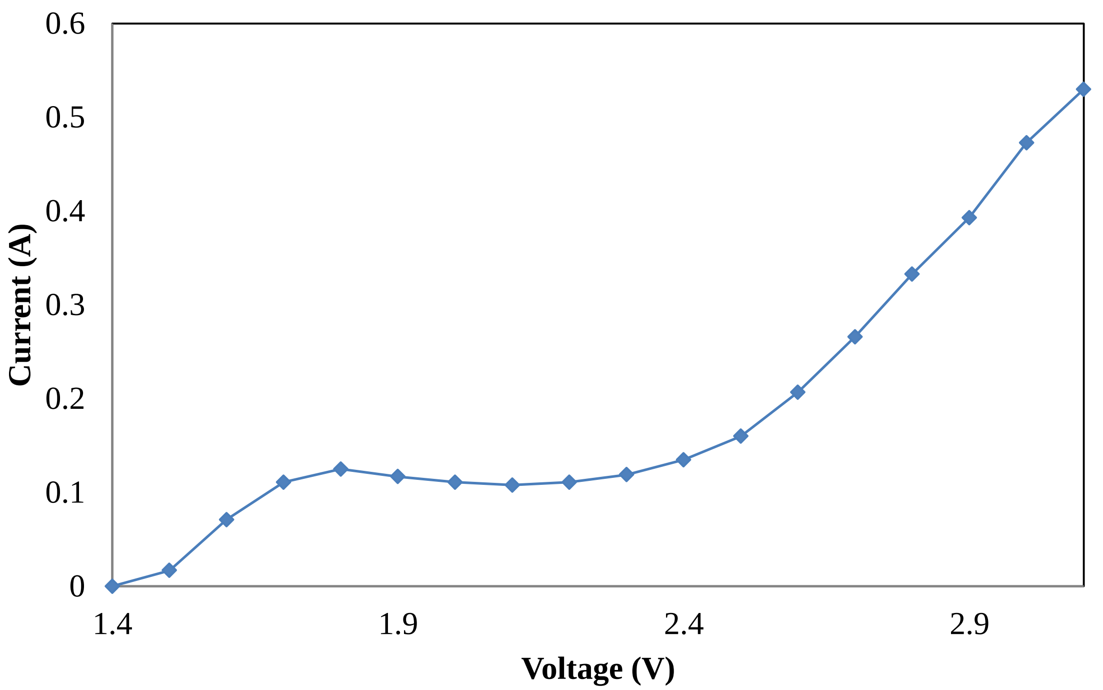


Figure 24 – Current vs Voltage for 20% Sodium Chloride solution at -5°C as Electrolyte; Experiment Standard Deviation – 7%

For 20% Sodium chloride solution as an electrolyte at -5°C, the peak power value was 1.64W which was also the rated power in this case.

4.1.4 NaCl (20% Solution) at -10°C

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at -10°C when the electrolyte used was 20% solution of sodium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in table 7. From this data, the values of Power and Hydrogen Production were computed and plotted.

Voltage (V)	**Current (A)**	**Time (s)**	**Hydrogen Production Rate (ml/min)**
1.4	0	300	0
1.5	0	300	0
1.6	0	300	0
1.7	0	300	0
1.8	0	300	0
1.9	0	300	0
2	0	300	0
2.1	0	300	0
2.2	0.01	300	0
2.3	0.02	300	0
2.4	0.04	300	0.2
2.5	0.09	300	0.4
2.6	0.17	300	2.2
2.7	0.26	300	1.4
2.8	0.37	300	3.2
2.9	0.46	300	3.6
3	0.5	300	4.4
3.1	0.57	300	4.6

Table 7 – Hydrogen Production Rate for 20% Sodium chloride solution at -10°C as Electrolyte

The results from the experiment show that for the given Horizon PEM electrolyzer, there is no current for an input voltage of 1.4V. When the voltage was increased to 1.6V there was a very meagre amount of current in the circuit and no rate of hydrogen production over duration of 5 min. The value of current remains below 0.01A till the input voltage was 2.1V. But when the voltage was increased to 2.6V, there was an increase in the value of current and also noticeable hydrogen production over 5 min duration. The value of current increased up to 3.1V, after which it was dropped, where the experiment was stopped since the given Electrolyzer was rated only to 3V. A graph of current vs voltage, hydrogen production rate vs voltage power and hydrogen production rate vs power input were plotted. It was observed that maximum rate of hydrogen production remained at 5 ml/min when the electrolyte used was 20% sodium chloride solution at -10°C compared to the salt solution at -5°C.

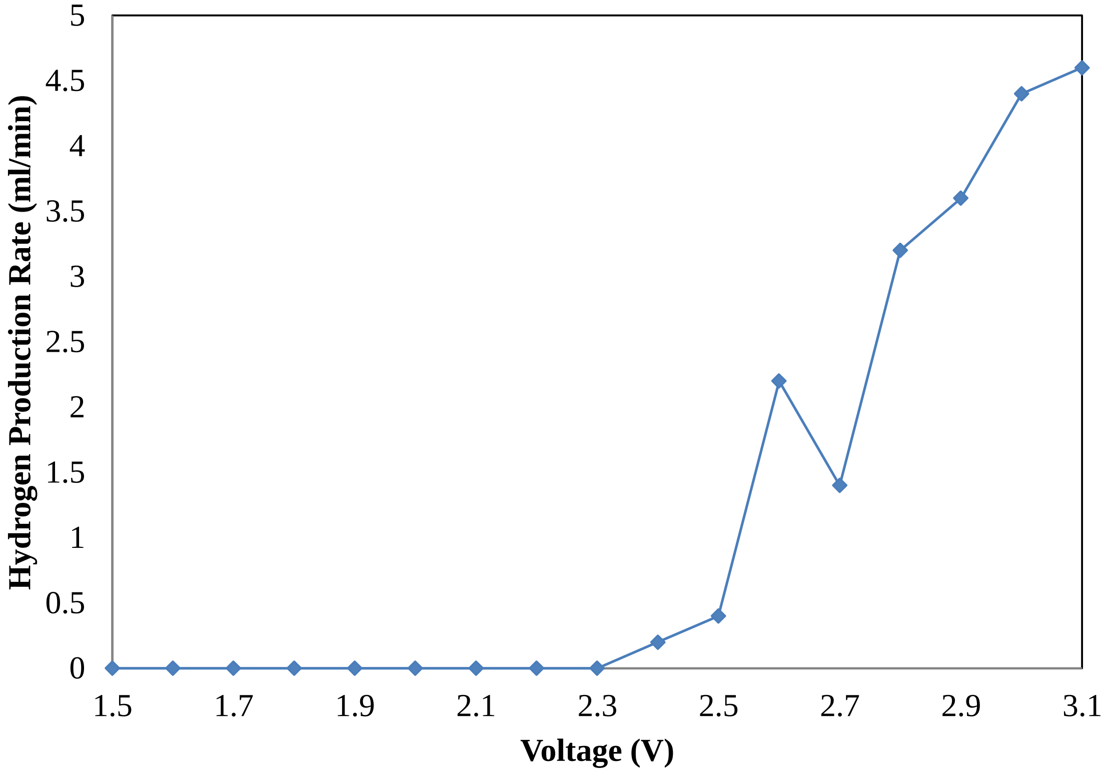


Figure 25 - Hydrogen Production Rate vs Voltage for 20% Sodium Chloride solution at -10°C Electrolyte; Experiment Standard Deviation – 9%

For 20% Sodium chloride solution as an electrolyte at -5°C, the peak power value was 1.77W which was also the rated power in this case.

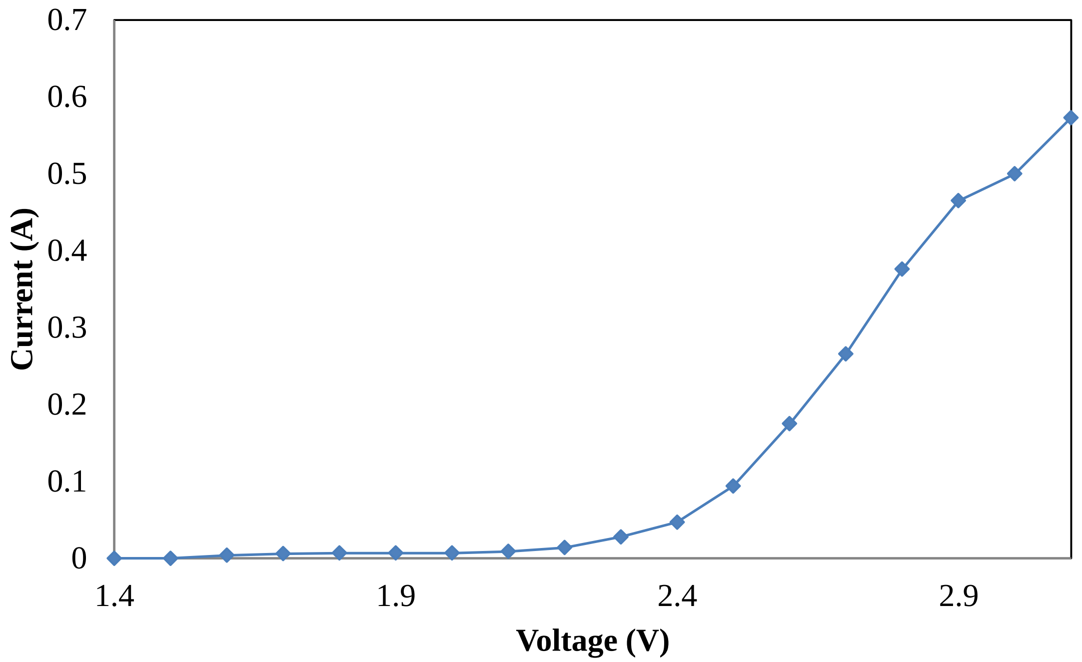


Figure 26 – Current vs Voltage for 20% Sodium Chloride solution at -10°C as Electrolyte; Experiment Standard Deviation – 9%

4.1.5 LiCl (10% Solution) at Standard Room Temperature and Pressure

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at standard pressure and temperature when the electrolyte used was 10% solution of lithium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in Table 8. From this data, the values of Power and Hydrogen Production were computed and plotted.

The results from the experiment show that for the given Horizon PEM electrolyzer, there is a very meagre amount of current for an input voltage of 1.5V. When the voltage was increased to 1.6V there was a noticeable current and a very small hydrogen production rate over duration of 5 min. After which the value of current increased and stayed around 0.2A – 0.3A where the production rate was around 3 – 4 ml/min. Graph of current vs voltage, hydrogen production rate vs voltage power and hydrogen production rate vs power input were plotted. It was observed that maximum rate of hydrogen production increased to 7.4 ml/min when the electrolyte used was 10% lithium chloride solution.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0.00	300	0
1.5	0.01	300	0
1.6	0.07	300	0.4
1.7	0.11	300	1.2
1.8	0.20	300	2.4
1.9	0.28	300	2.6
2	0.25	300	1.8
2.1	0.24	300	3.6
2.2	0.27	300	3
2.3	0.25	300	2
2.4	0.30	300	3.8
2.5	0.29	300	3.8
2.6	0.29	300	4
2.7	0.33	300	4
2.8	0.33	300	4
2.9	0.32	300	4
3	0.40	300	4.3
3.1	0.47	300	7.4

Table 8 – Hydrogen Production Rate for 10% Lithium chloride solution as Electrolyte at STP

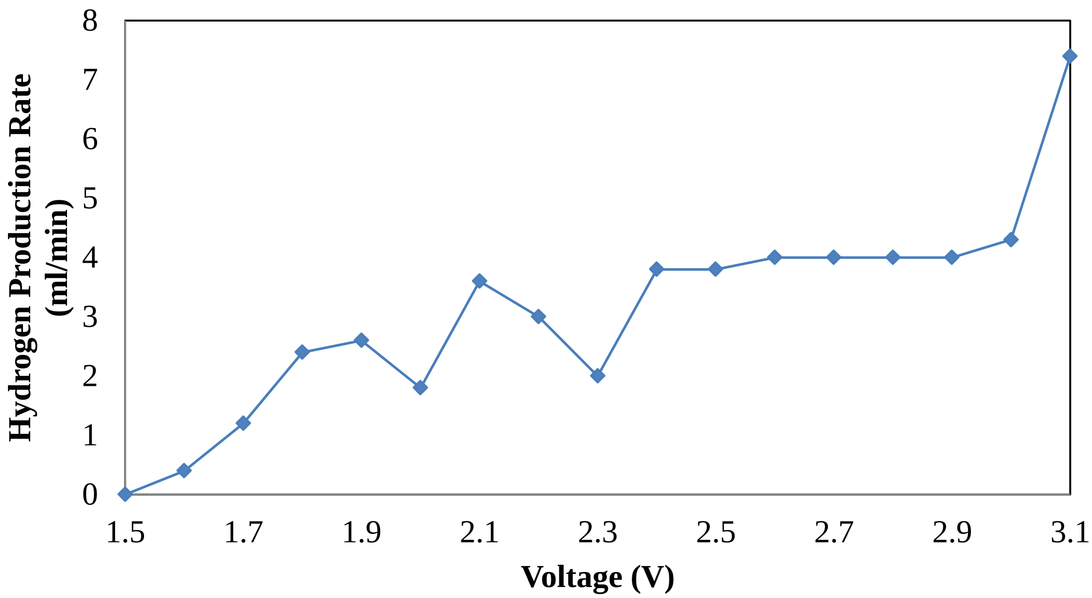


Figure 27 – Hydrogen Output Vs Power Input for 10% Lithium Chloride solution as Electrolyte at STP; Experiment Standard Deviation – 6%

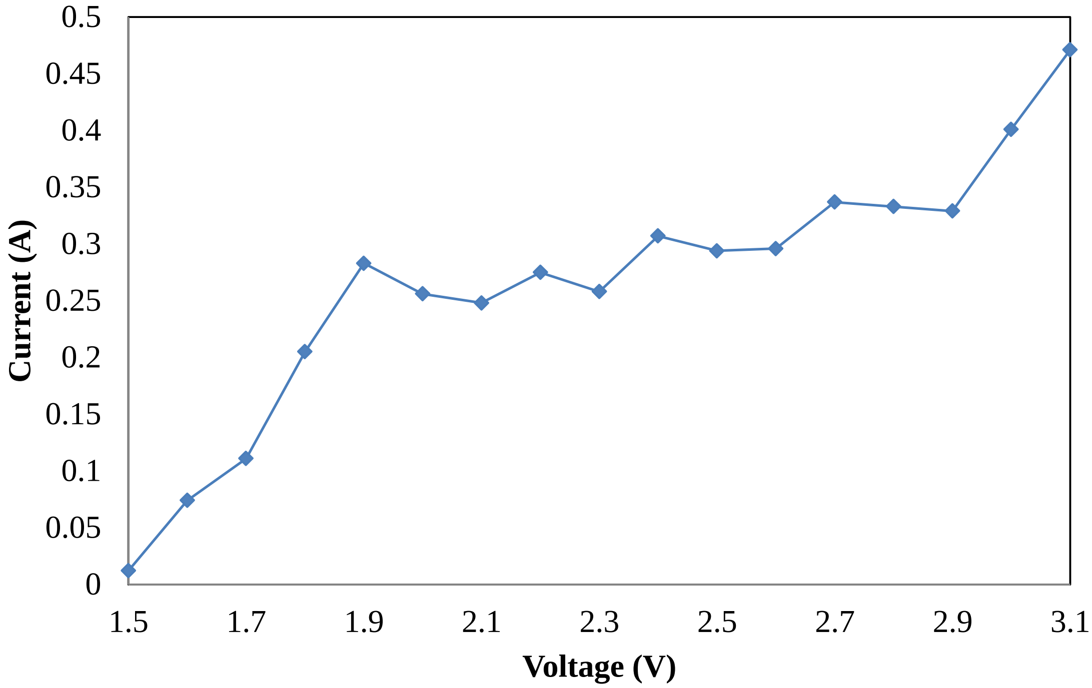


Figure 28 - Current vs Voltage for 10% Lithium Chloride solution as Electrolyte at STP; Experiment Standard Deviation – 6%

For 10% Lithium chloride solution as an electrolyte at STP, the peak power value was 1.46W which was also the rated power in this case.

4.1.6 LiCl (10% Solution) at -5°C

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at -5°C when the electrolyte used was 10% solution of lithium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in table 9. From this data, the values of Power and Hydrogen Production were computed and plotted.

The results from the experiment show that for the given Horizon PEM electrolyzer, the value of current is very low till 1.5V. When the voltage was increased to 1.6V there was a noticeable rate of hydrogen production over duration of 5 min. The value of current increased linearly till 2.2V. The value of current remained constant around 0.3-0.4A from 2.3V to 3.1V, where the value of hydrogen production rate fluctuated between 3.5 – 5.5 ml/min. At 3.1V the value of current along with the hydrogen production rate decreased, where the experiment was stopped since the given Electrolyzer was rated only to 3V. A graph of hydrogen production rate vs voltage and current vs voltage were plotted in figures 28 and 29 respectively.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0.00	300	0
1.5	0.02	300	0
1.6	0.11	300	0.2
1.7	0.24	300	1.8
1.8	0.37	300	2.5
1.9	0.50	300	4.1
2	0.66	300	6
2.1	0.69	300	5.6
2.2	0.80	300	6
2.3	0.60	300	6.2
2.4	0.39	300	4.2
2.5	0.30	300	4
2.6	0.32	300	3.8
2.7	0.38	300	4
2.8	0.41	300	5.4
2.9	0.33	300	5.6
3	0.33	300	4
3.1	0.30	300	3.6

Table 9 – Hydrogen Production Rate for 10% Lithium chloride solution at -5°C as Electrolyte

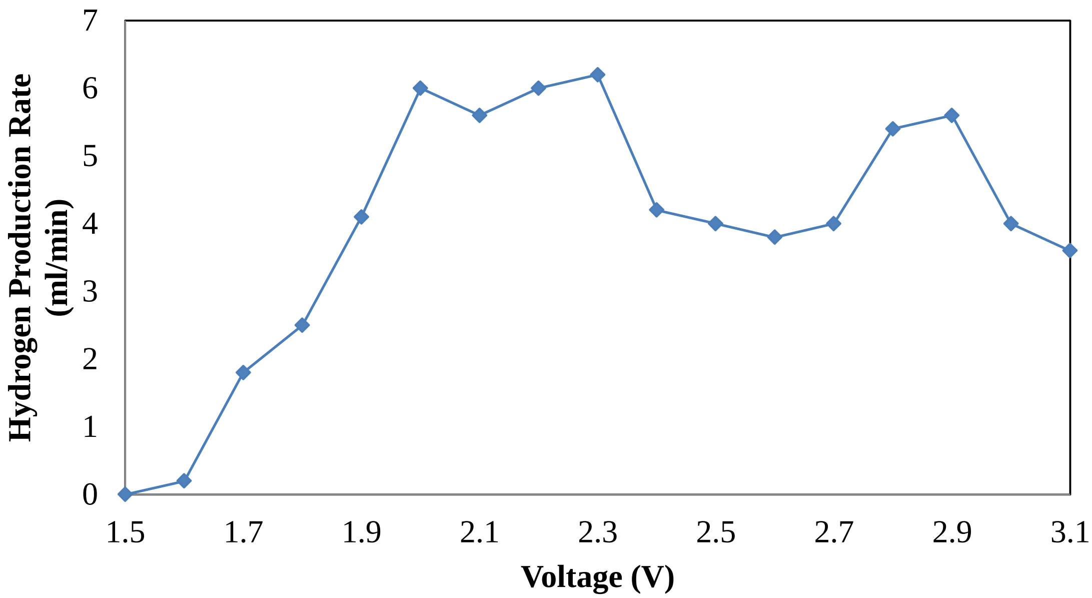


Figure 29 - Hydrogen Production Rate vs Voltage for 10% Lithium Chloride solution at -5°C as Electrolyte; Experiment Standard Deviation – 5%

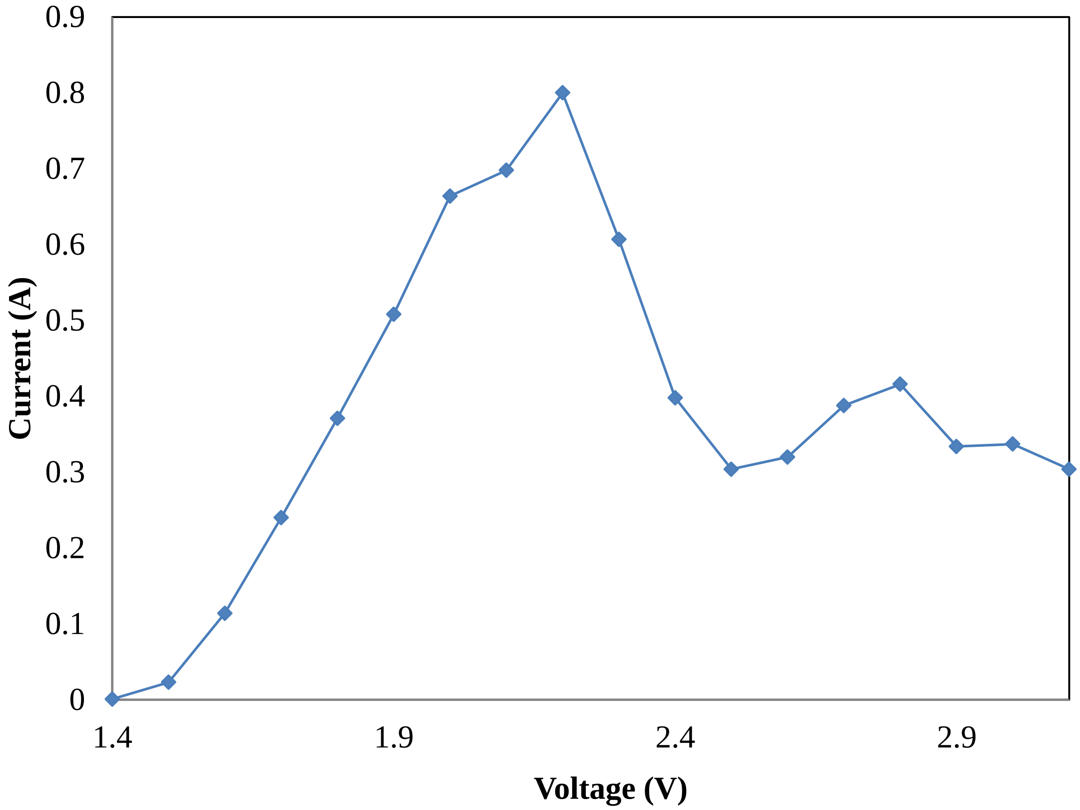


Figure 30 – Current vs Voltage for 10% Lithium Chloride solution at -5°C as Electrolyte; Experiment Standard Deviation – 5%

It was observed that maximum rate of hydrogen production was 6 ml/min. For 10% Lithium chloride solution as an electrolyte at -5°C, the peak power value was 1.76W and the rated power was 1.39W.

4.1.7 LiCl (10% Solution) at -10°C

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at -10°C when the electrolyte used was 10% solution of lithium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in table 10. From this data, the values of Power and Hydrogen Production were computed and plotted. The results from the experiment show that for the given Horizon PEM electrolyzer, there is no current for an input voltage of 1.4V. When the voltage was increased to 1.6V there was a very meagre amount of current in the circuit and hydrogen production rate of 1ml/min over duration of 5 min. The value of current increased linearly up to 2.3V. A graph of hydrogen production rate vs voltage and current vs voltage were plotted in figures 30 and 31 respectively.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0.00	300	0
1.5	0.01	300	0
1.6	0.11	300	1
1.7	0.25	300	1
1.8	0.39	300	3.6
1.9	0.53	300	4
2	0.69	300	4.8
2.1	0.69	300	6.4
2.2	0.8	300	5.1
2.3	1.00	300	8
2.4	0.88	300	7.7
2.5	0.50	300	5
2.6	0.44	300	5
2.7	0.44	300	5
2.8	0.45	300	4.8
2.9	0.46	300	4.2
3	0.44	300	4.6
3.1	0.49	300	7

Table 10 – Hydrogen Production Rate for 10% Lithium chloride solution at -10°C as Electrolyte

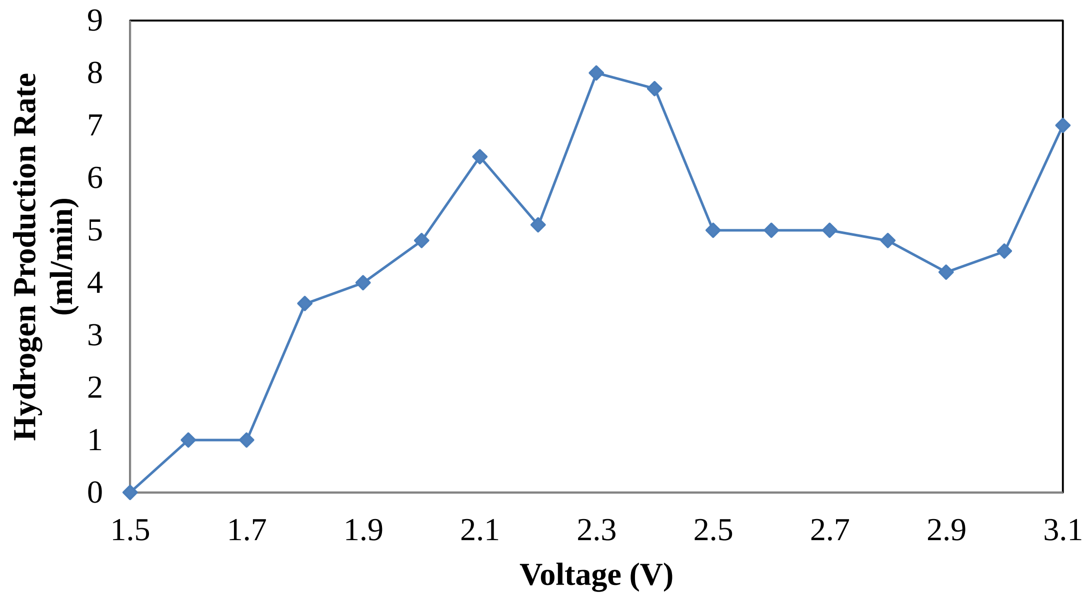


Figure 31 - Hydrogen Production Rate vs Voltage for 10% Lithium Chloride solution at -10°C Electrolyte; Experiment Standard Deviation – 7%

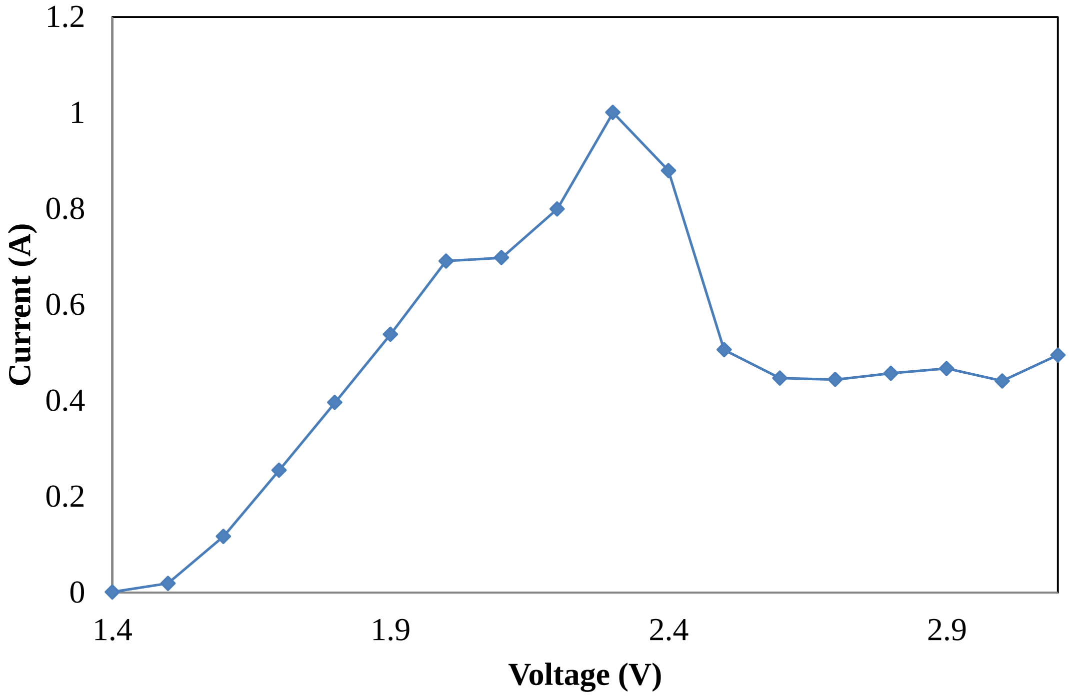


Figure 32 – Current vs Voltage for 10% Lithium Chloride solution at -10°C as Electrolyte; Experiment Standard Deviation – 7%

It was observed that maximum rate of hydrogen production was 8 ml/min. For 10% Lithium chloride solution as an electrolyte at -5°C, the peak power value was 2.3W which was equal to the rate power as well in this case.

4.1.8 LiCl (20% Solution) at Standard Room Temperature and Pressure

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at standard pressure and temperature when the electrolyte used was 20% solution of lithium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in Table 11. From this data, the values of Power and Hydrogen Production were computed and plotted.

The results from the experiment show that for the given Horizon PEM electrolyzer, there is a very meagre amount of current for an input voltage of 1.5V. When the voltage was increased to 1.6V there was a noticeable current and a very small hydrogen production rate over duration of 5 min. The current increased linearly in very small amounts upto 3.1V. Graph of current vs voltage, hydrogen production rate vs voltage power and hydrogen production rate vs power input were plotted.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0	300	0
1.5	0.01	300	0
1.6	0.06	300	0.8
1.7	0.08	300	0.4
1.8	0.06	300	0.8
1.9	0.07	300	1.3
2	0.08	300	0.4
2.1	0.09	300	1.8
2.2	0.1	300	0.6
2.3	0.10	300	2
2.4	0.11	300	0.8
2.5	0.11	300	0.7
2.6	0.14	300	2.6
2.7	0.15	300	2.8
2.8	0.14	300	1.6
2.9	0.16	300	2.2
3	0.18	300	2.4
3.1	0.18	300	2.4

Table 11 – Hydrogen Production Rate for 20% Lithium chloride solution as Electrolyte at STP

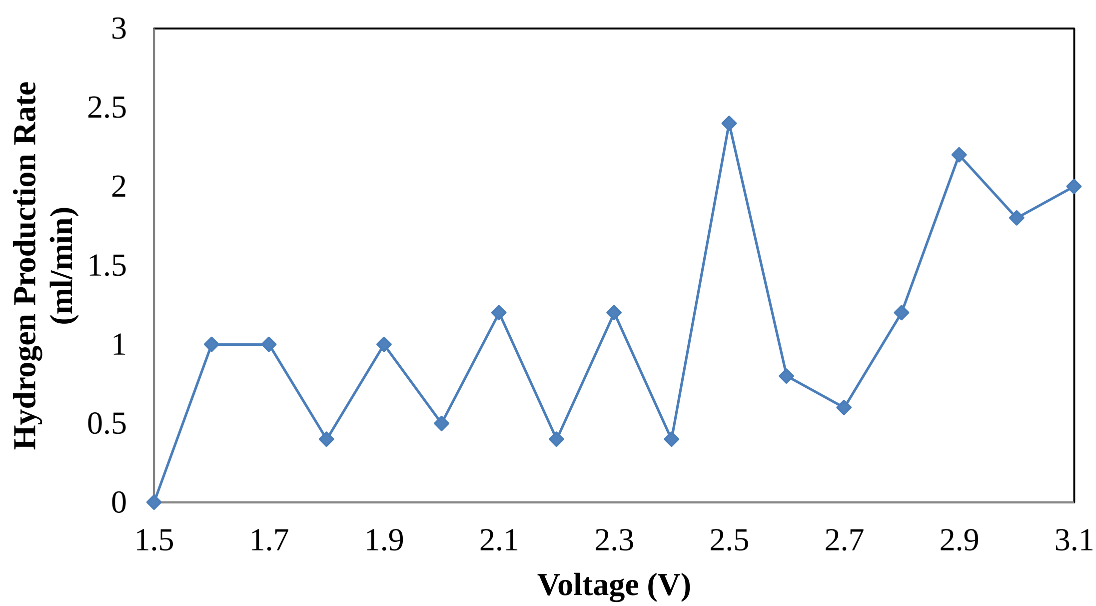


Figure 33 – Hydrogen Output Vs Power Input for 20% Lithium Chloride solution as Electrolyte at STP; Experiment Standard Deviation – 5%

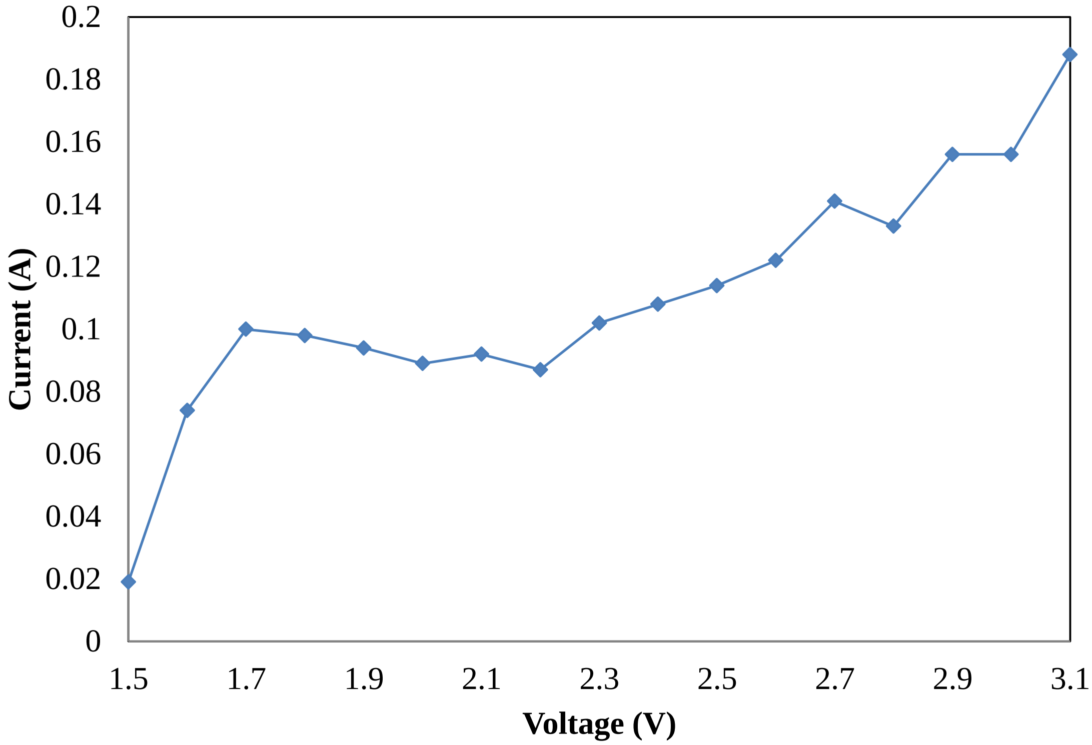


Figure 34 - Current vs Voltage for 20% Lithium Chloride solution as Electrolyte at STP; Experiment Standard Deviation – 5%

For 20% Lithium chloride solution as an electrolyte at STP, the peak power value is 0.58W and the rated power is 0.28W.

4.1.9 LiCl (20% Solution) at -5°C

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at -5°C when the electrolyte used was 20% solution of lithium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in table 12. From this data, the values of Power and Hydrogen Production were computed and plotted.

The results from the experiment show that for the given Horizon PEM electrolyzer, there is a very meagre amount of current for an input voltage of 1.5V. When the voltage was increased to 1.6V there was a noticeable current and a very small hydrogen production rate over duration of 5 min. The current increased linearly in very small amounts upto 3.1V. Graph of current vs voltage, hydrogen production rate vs voltage power and hydrogen production rate vs power input were plotted.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0.00	300	0
1.5	0.01	300	0.2
1.6	0.06	300	0.4
1.7	0.12	300	0.3
1.8	0.14	300	1
1.9	0.15	300	2.5
2	0.16	300	0.5
2.1	0.14	300	1.7
2.2	0.17	300	2
2.3	0.17	300	1
2.4	0.23	300	2.7
2.5	0.22	300	1.2
2.6	0.22	300	2.9
2.7	0.24	300	1.8
2.8	0.27	300	2.5
2.9	0.26	300	2.3
3	0.33	300	2
3.1	0.40	300	3.8

Table 12 – Hydrogen Production Rate for 20% Lithium chloride solution at -5°C as Electrolyte

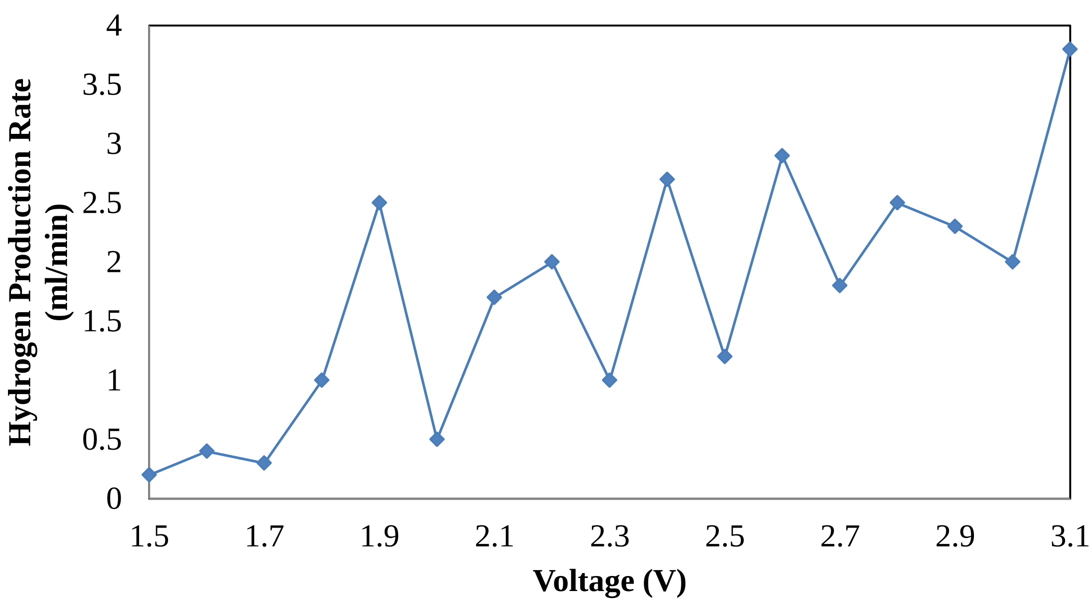


Figure 35 - Hydrogen Production Rate vs Voltage for 20% Lithium Chloride solution at -5°C as Electrolyte; Experiment Standard Deviation – 7%

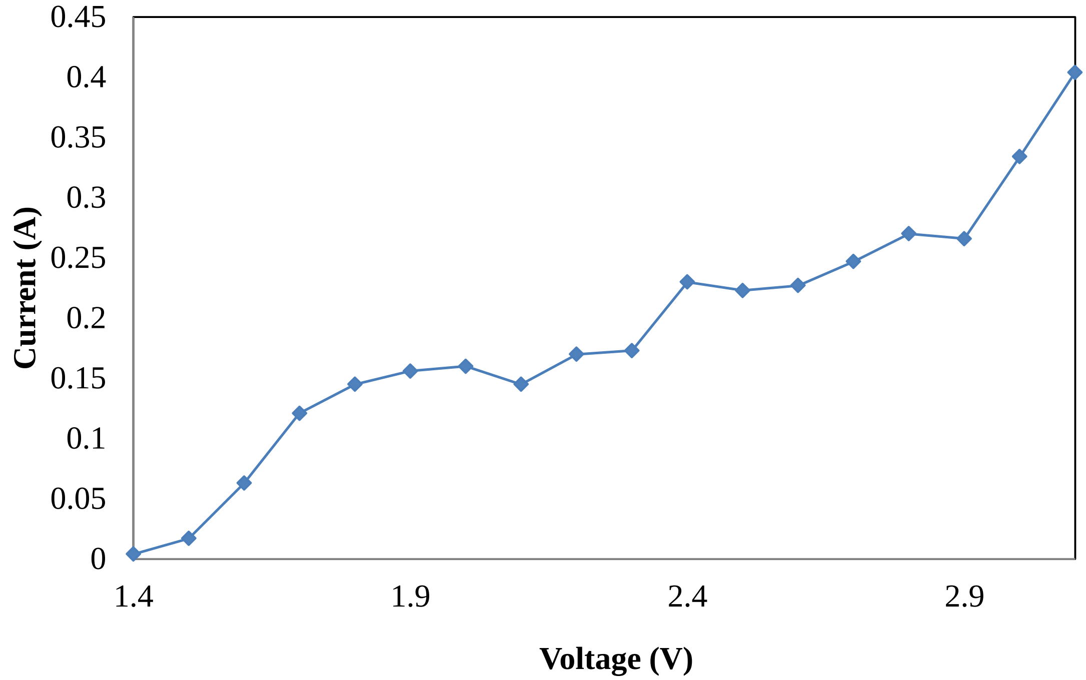


Figure 36 – Current vs Voltage for 20% Lithium Chloride solution at -5°C as Electrolyte; Experiment Standard Deviation – 7%

It was observed that maximum rate of hydrogen production was 6 ml/min. For 20% Lithium chloride solution as an electrolyte at -5°C, the peak power value was 1.25W which is also equal to the rated power.

4.1.10 LiCl (20% Solution) at -10°C

As discussed in the earlier chapter, another experiment was conducted to evaluate the performance of a Horizon PEM electrolyzer at -20°C when the electrolyte used was 10% solution of lithium chloride (ACS grade). The values of Current and Water Displacement rate were tabulated as shown in table 10. From this data, the values of Power and Hydrogen Production were computed and plotted. The results from the experiment show that for the given Horizon PEM electrolyzer, there is no current for an input voltage of 1.4V. When the voltage was increased to 1.6V there was a very meagre amount of current in the circuit and hydrogen production rate of 1ml/min over duration of 5 min. The value of current increased linearly up to 3.1V. A graph of hydrogen production rate vs voltage and current vs voltage were plotted in figures 37 and 38 respectively.

Voltage (V)	Current (A)	Time (s)	Hydrogen Production Rate (ml/min)
1.4	0.00	300	0
1.5	0.01	300	0
1.6	0.07	300	0.2
1.7	0.13	300	2
1.8	0.18	300	1.6
1.9	0.18	300	1.2
2	0.19	300	1
2.1	0.19	300	2.6
2.2	0.20	300	0.6
2.3	0.21	300	2.2
2.4	0.24	300	1.6
2.5	0.24	300	2.4
2.6	0.26	300	1.8
2.7	0.28	300	2.4
2.8	0.31	300	1.6
2.9	0.34	300	3.8
3	0.39	300	2.8
3.1	0.44	300	3.2

Table 13 – Hydrogen Production Rate for 20% Lithium chloride solution at -10°C as Electrolyte

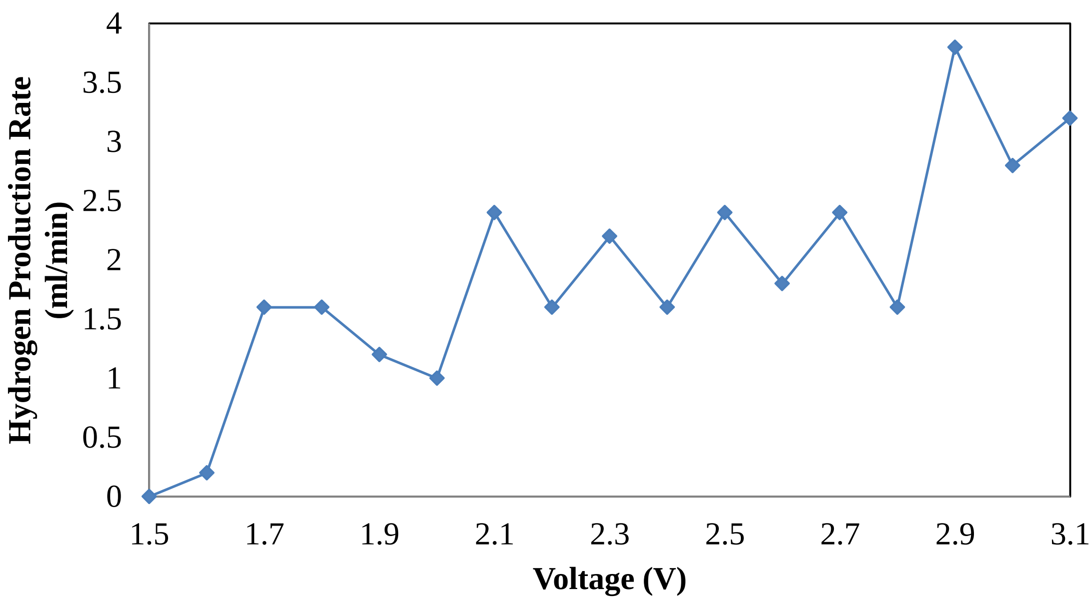


Figure 37 - Hydrogen Production Rate vs Voltage for 20% Lithium Chloride solution at -10°C Electrolyte; Experiment Standard Deviation – 9%

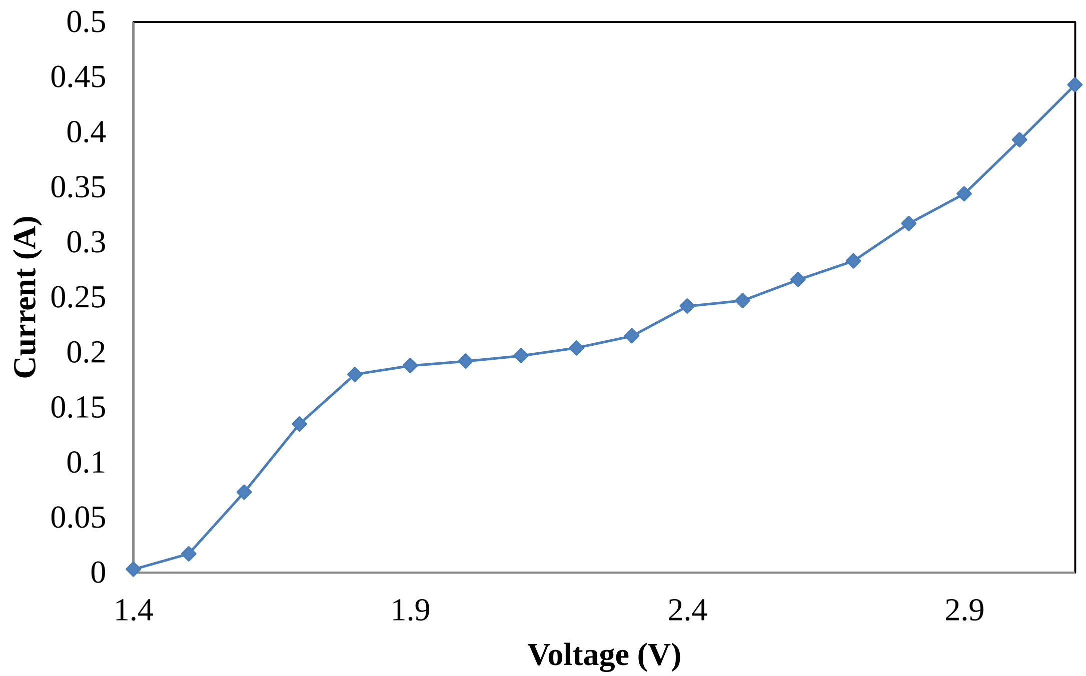


Figure 38 – Current vs Voltage for 20% Lithium Chloride solution at -10°C as Electrolyte; Experiment Standard Deviation – 9%

It was observed that maximum rate of hydrogen production was 4 ml/min. For 20% Lithium chloride solution as an electrolyte at -5°C, the peak power value was 1.3Wand the rated power is 1W.

4.2 Comparison of Electrolytes at Different Temperatures

4.2.1 20% Sodium Chloride Solution

The figure 39 shows that a 20% sodium chloride solution at room temperature performs equivalent to that of distilled water at STP. But at -5°C and -20°C, the PEM electrolyzer requires higher voltage to produce substantial amount of hydrogen.

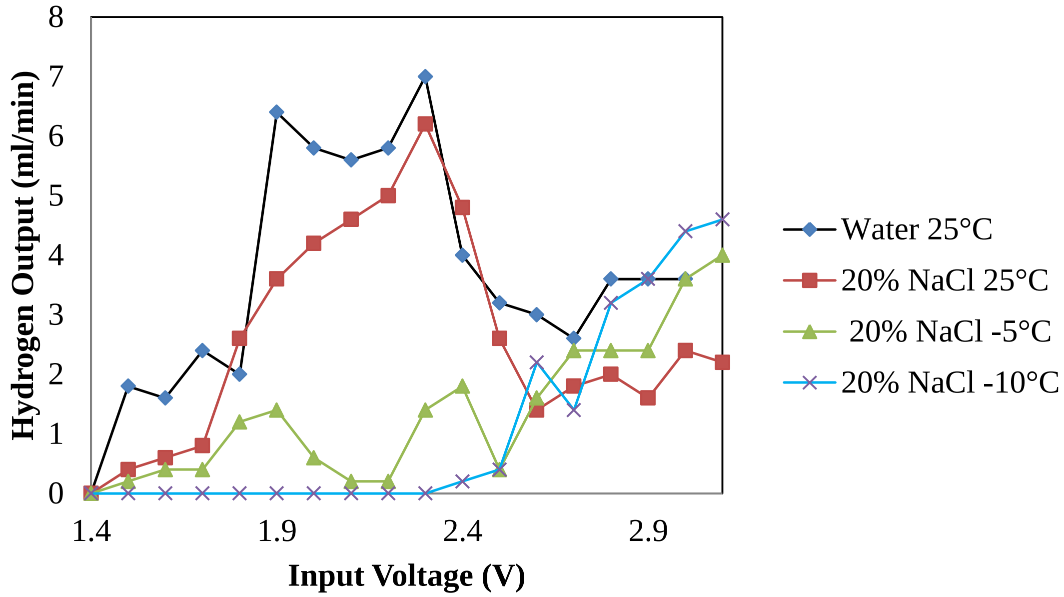


Figure 39 – 20% Sodium Chloride Solution as Electrolyte at Different Temperature

4.2.2. 10% Lithium Chloride Solution

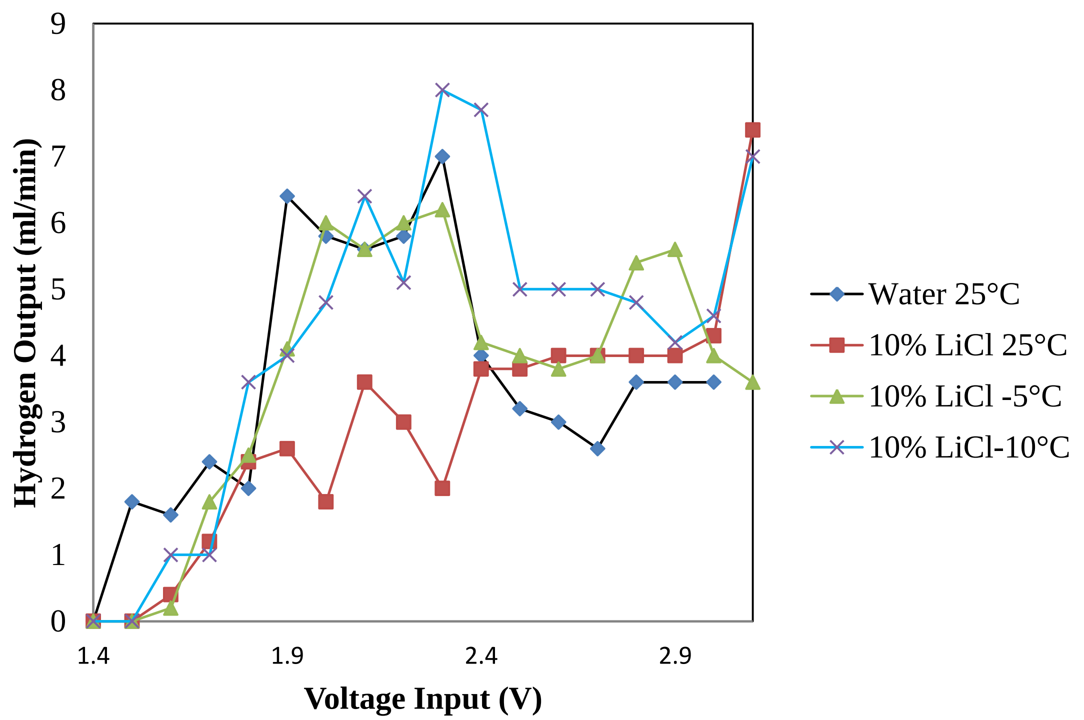


Figure 40 – 10% Lithium Chloride Solution as Electrolyte at Different Temperature

From figure 40, it can be observed that a 10% Lithium chloride solution performs below par at STP when compared to distilled water. But, at negative temperatures lithium chloride produces results which are either better or equal to that of distilled water at STP. The other trend that remains constant is the increased production of hydrogen at lower temperatures with higher input voltage.

4.2.3 20% Lithium Chloride Solution

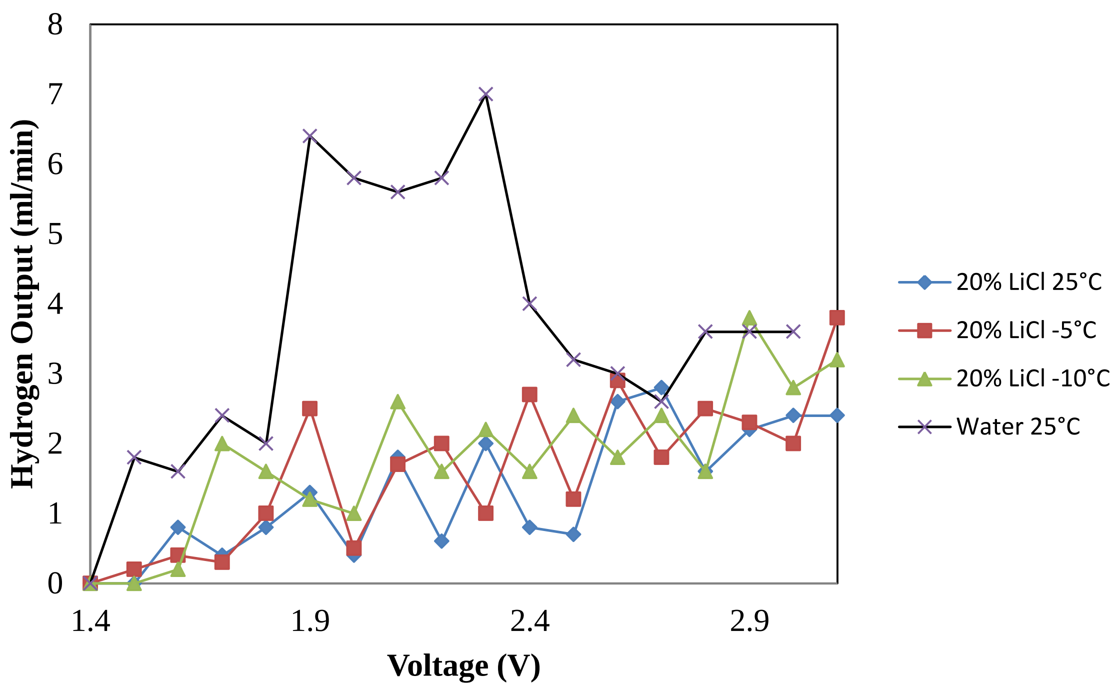


Figure 41 – 20% Lithium Chloride Solution as Electrolyte at Different Temperature

In the above figure 41, it can be seen that the behavior of PEM electrolyzer with 20% Lithium chloride solution as electrolyte does not vary with temperature. It can be seen that with a higher voltage 20% Lithium Chloride solution can produce hydrogen up to the rate of 4ml/min.

In figure 42, the comparison of maximum hydrogen production rate for different concentrations of solutions at different temperatures is shown. It can be seen that rate of hydrogen production increases with drop in temperature for Lithium chloride, whereas the hydrogen output has decreased with temperature for Sodium chloride.

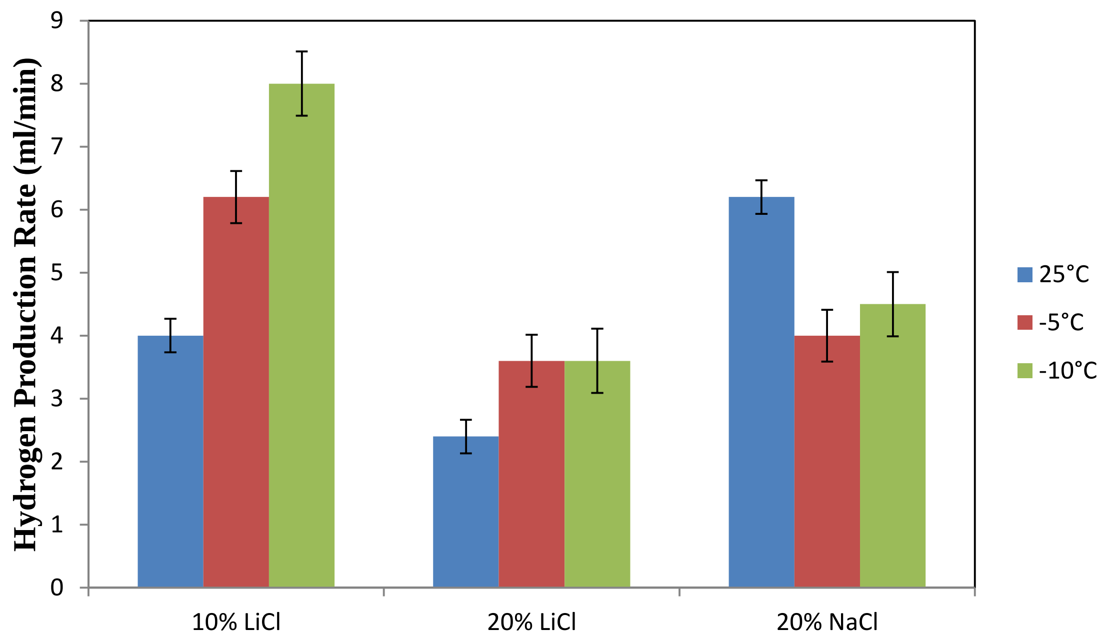


Figure 42 – Comparison of Maximum Hydrogen Production Rate

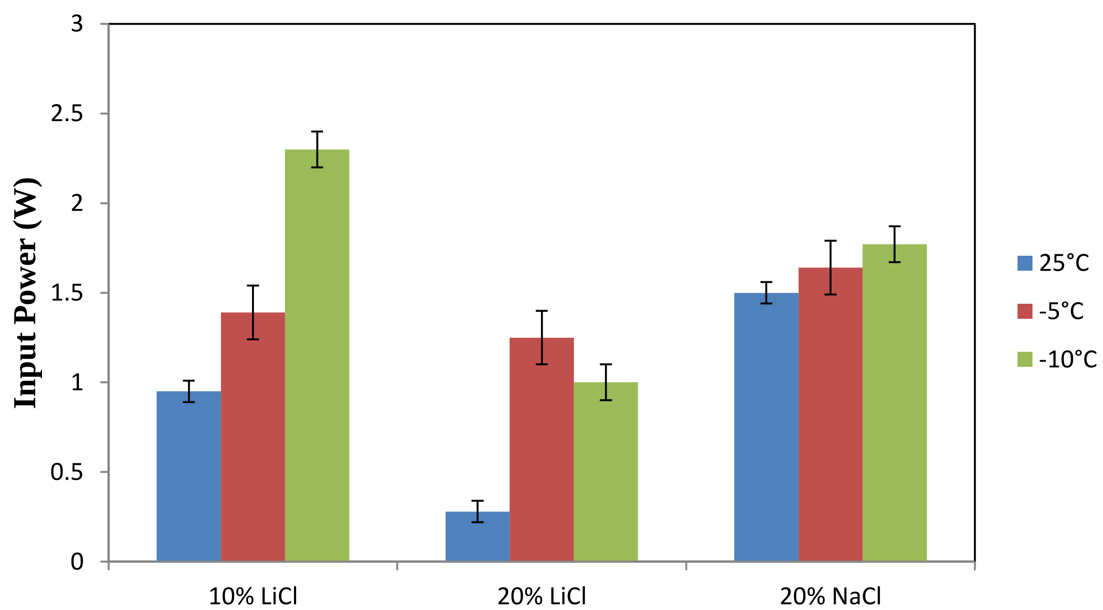


Figure 43 – Comparison of Power Input for Maximum Hydrogen Production Rate

In figure 43, the comparison of input power required for the PEM electrolyzer at maximum hydrogen production rate for various concentrations of solutions at different temperatures is shown. It can be seen that input power increases with drop in temperature for both Lithium Chloride and Sodium chloride solutions.

4.3 Summary

Feasibility analysis suggests that the proposed PVEPS is superior to other propulsion options available for CubeSats because it provides much higher ΔV and is safe as shown in Table 2. 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 [2]. Zeeldon and Peck's system is designed to perform orbit raising maneuvers. A scaled up version of this system to a 14kg 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 be still be restricted to navigating within the earth's gravity well. 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, require thermal insulation and 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.

Condition	Junction Temperature(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

Table 14 – Heat Energy Requirements for 6U CubeSat unit at LEO

Table 1 lists the power required in terms of keeping a 14kg 6U CubeSat at 297K. 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 use of 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.

Further, Zeledon and Peck system does not account for the separation of hydrogen and oxygen after the gases have been electrolyzed. The electrolyzed gases are collected in the same chamber where they are stored before combustion. Premixing f 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 premising 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) [30]. This system offers thrust by 4 1N rocket engines. The total mass of the propulsion system is 3.2kg including propellant of mass 1.2kg. This system occupies 10x10x23 cm and operates in a temperature range of +5 to +50°C. A schematic view of the system is shown in Figure 1. This system makes use of Hydrazine as propellant with a thrust of 2.79N impulse of 0.004Ns per thruster. This system was designed for specific mission such as orbit maintenance and attitude control. The ΔV and thrust provided by this system is not sufficient for orbit raising.

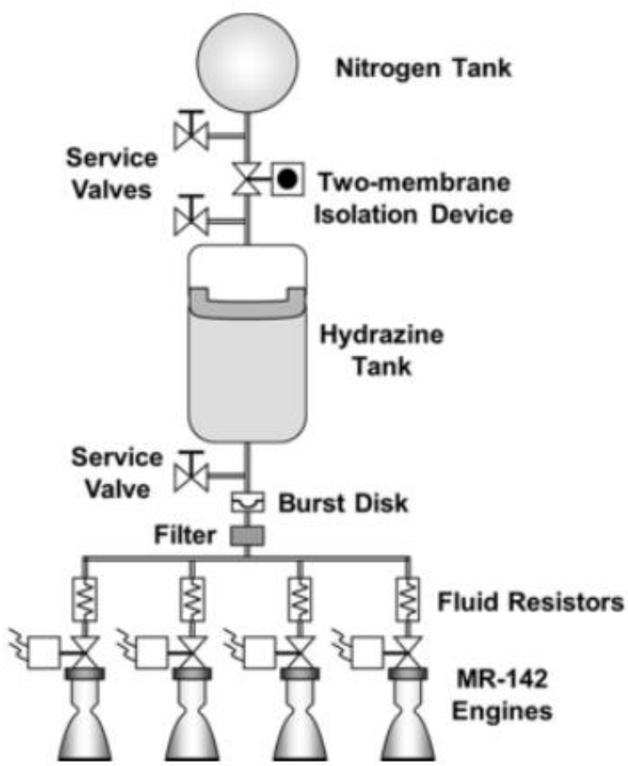


Figure 42- Schematic of MPS 120 [30]

The use of Hydrazine as a propellant increases challenges with regard to safety. It is highly toxic and dangerously unstable in anhydrous form. According to the U.S Environment Protection Agency it causes vital damage to human beings when exposed. All this means that much more care and complexity at the University level is required when designing a system which makes use of Hydrazine as a propellant.

A cold gas thruster that can be implemented would only produce a ΔV of 20m/s, which is only sufficient for attitude control. The performance of cold gas thrusters is largely dependent on the pressurized chamber it is stored in. Since CubeSat Design Standard does not allow for pressurized vessels due to safety concerns, this rules out the use of cold gas propulsion system for orbit raising. The performance comparison with pros and cons for the individual missions has been summarized into Table 2.

System	**ΔV**	**Thrust**	**Thermal Insulation**	**Safety**	**Restrictions**
Photovoltaic Electrolysis Propulsion System (H2O)	4000 m/s	8.5N	Freezing Point Depression of electrolyte helps avoid energy for heating.	Green propellant Separate tanks for H_2 and O_2.	Propellant carried
Electrolysis Propulsion By Mason Peck and Zeledon	850 m/s	5N	Requires heat energy from external power source.	Green Propellant Same tank for H_2 and O_2.	Not functional beyond Earth's gravity well Propellant carried
CubeSat Modular Propulsion System (Hydrazine)	550 m/s	4N 4 Thrusters of 1N each	Requires thermal insulation since operating condition is between 5-50°C.	Highly toxic propellant	Operating conditions Propellant carried
Cold Gas Thruster System (Nitrogen)	20 m/s	1.5N	Requires thermal insulation to maintain pressure	Inert Propellant	Only for Attitude Control Pressure dependent

Table 15 –Comparison of CubeSat Propulsion Systems

Based on these results, our proposed electrolysis system offers an 8 fold increase in high impulse ΔV compared to current commercial systems. This is because the PVEPS's design enables it to carry much more propellant than any other propulsion system designed for CubeSats. The extra green propellant comes from mass savings in the system. One such example is avoiding a cooling mechanism for the thrust chamber. Since the thrust chamber is surrounded by the propellant, heat transfer from the combustion chamber to the propellant tank ensures cooling of the thrust chamber. This system does not have to carry fuel and oxidizer separately. They are combined and stored in the form of water which breaks down to give the required fuel and oxidizer when necessary. Freezing point depression of water avoids the use of a heating system which would add substantial mass and complexity to the design.

Though the experimental results show that the rate of hydrogen production has decreased due to the use of salt solutions, PVEPS is designed to mitigate this minor issue. Since PVEPS has multiple units of electrolyzers unlike any other electrolysis propulsion system, the required hydrogen and oxygen gases will be collected in much lesser time compared to other systems. Also, multiple units of electrolyzers offer for redundancy in the system.

In addition it is expected to offer a 5 fold advantage over the best proposed electrolysis systems. The fact that this system uses a green propellant makes it environment friendly and one for the future. The system offers increased operational flexibility over its other counterparts because of its unique design. One such instance is the use of a reaction wheel to generate spin over magnetic torquers. This enables the spacecraft to spin and operate normally even outside the earth's magnetic field. The other advantage comes from the significant energy savings possible in not having to heat the propellant. Since the system stores oxygen and hydrogen in different storage tanks it eliminates the chance of any uncontrolled combustion. The options of increasing salt content or using other options such borax or ionic solutions to further lower freezing point gives much more potential to the PVEPS. All this translates significantly higher ΔV, increased flexibility in mission design and increased safety.

4.4 Contribution

The design and development of PVEPS would not have been possible without the study of previous research and other commercial developments. Though these have laid the foundation for the system, here are the significant contributions to this research:

- Use of separate storage tanks for Hydrogen and Oxygen to improve the functionality of the system.
- Concept of spinning only the propulsion section with respect to payload and electronics by use of micro reaction wheel

- Utilizing the concept of freezing point depression for storing propellant in CubeSats at negative temperatures.
- Design parameters for the construction of Thrust Chamber
- Experimental setup to demonstrate electrolysis when the electrolyte is in negative temperature

CHAPTER 5

CONCLUSION

5.1 Conclusion

An innovative propulsion solution was designed and developed which uses energy generated by on board photovoltaic panels to electrolyze water, thus producing combustible hydrogen and oxygen for low-thrust applications. Water has a high storage density allowing for sufficient fuel within volume constraints. Its high enthalpy of formation provides more fuel that translates into increased ΔV and vastly reduces risk for the launch vehicle.

The innovative technology used in the system overcame significant challenges mentioned earlier. The problem of water freezing was addressed by additives to depress freezing point of water which is a far more reliable solution. The power saved here can be used to fire attitude control micro- thrusters.

An efficient way of gas separation from liquid water in micro gravity environment was conceived and designed. It also helped provide additional stability to the entire spacecraft by cancelling out any torque generated by the operation of the thrust chamber.

5.2 Future Work

The future work of Photovoltaic Electrolysis Propulsion System (PVEPS) can mainly focus on:

1. To test the process of electrolysis at much lower temperatures to the tune of -200°C for various electrolyte solutions.
2. To test the process of electrolysis at micro gravity environments with the help of a thermal vacuum chamber.
3. To develop a custom designed PEM electrolyzer which is tailor made for the requirement of space missions.
4. Extensive testing of the reversible PEM Fuel cell using a fuel cell test station.
5. Design and testing of the thrust chamber by combusting the electrolyzed hydrogen and oxygen gases.
6. To test the efficiency of the PEM electrolyzer when additives to reduce corrosion are added to the salt solution.

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