AAS 17-145

HYDROS: HIGH PERFORMANCE WATER-ELECTROLYSIS PROPULSION FOR CUBESATS AND MICROSATS

Karsten James*, Maxwell Bodnar†, Mason Freedman ‡, Lars Osborne§, Richard Grist**, and Robert Hoyt††

The increasing availability of secondary payload flight opportunities has led to a dramatic expansion in the demand for small satellite propulsion systems. The HYDROS propulsion architecture couples a high performance (≥1.2 N / ≥310 s) bipropellant thruster with a high efficiency electrolyzer used to generate gaseous hydrogen and oxygen propellants on orbit through the electrolysis of water. The use of an 'inert' propellant — water — that is non-toxic, non-explosive, and does not require pressurized storage during launch reduces program costs and makes HYDROS propulsion systems ideal for secondary payload operations where risks to primary systems must be minimized. From this basic architecture TUI has designed two flight system variants, HYDROS-C for volume constrained or CubeSat scale missions, and HYDROS-M for MicroSat class missions. This paper details the basic capabilities of both variants of the HYDROS system, provides performance characterization of the HYDROS bipropellant thruster, and outlines system performance trades possible with the flexibility afforded by the hybrid electrical/chemical system.

INTRODUCTION

HYDROS is a novel high-TRL propulsion architecture that uses a hybrid electrical/chemical scheme to provide small spacecraft with both high thrust (≥1.2 N) and high I_{sp} (≥310 s) propulsion using a propellant that is non-toxic, non-explosive, and does not require pressurized storage during launch. HYDROS propulsion systems enable secondary payloads to perform missions requiring orbit agility and large ΔVs while launching with the ultimate 'green' propellant: water. Once on orbit the HYDROS system splits the water propellant using electrical power to produce hydrogen and oxygen gas. The evolved gases are then combusted in a bipropellant thruster to provide high-thrust propulsion or utilized as cold gas to provide minimum impulse-bit thrust events. Over the last four years Tethers Unlimited Inc. (TUI) has matured HYDROS to TRL-6 through a combination of government and commercial research and development efforts. TUI is currently readying two variants of the HYDROS propulsion system, HYDROS-C for CubeSats, and HYDROS-M for MicroSats, for flight with deliveries expected in 2017.

* Small Satellite Systems Program Manager, TUI, 11711 N Creek Pkwy S, Suite D113 Bothell, WA 98011, USA
† Aerospace Systems Engineer, TUI, 11711 N Creek Pkwy S, Suite D113 Bothell, WA 98011, USA
‡ Aerospace Engineer, TUI, 11711 N Creek Pkwy S, Suite D113 Bothell, WA 98011, USA
§ Mechanical Engineer, TUI, 11711 N Creek Pkwy S, Suite D113 Bothell, WA 98011, USA
** Aerospace Engineer, TUI, 11711 N Creek Pkwy S, Suite D113 Bothell, WA 98011, USA
†† Chief Scientist & CEO, TUI, 11711 N Creek Pkwy S, Suite D113 Bothell, WA 98011, USA

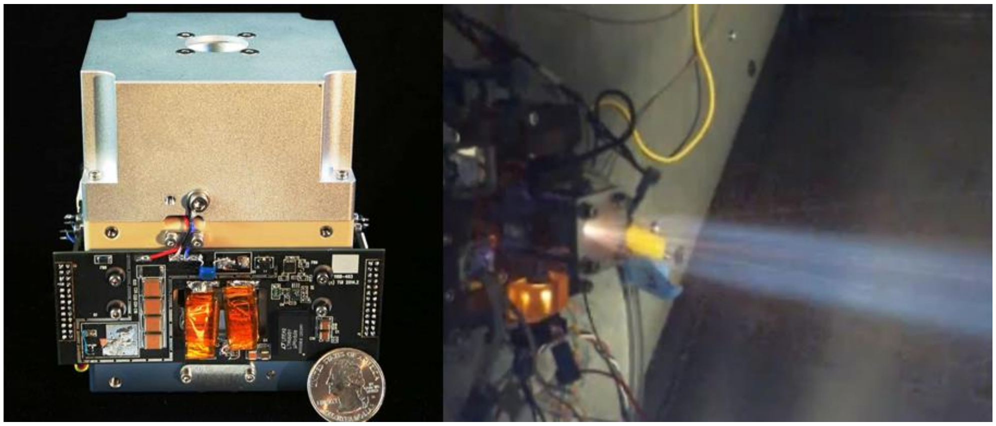


Figure 1. HYDROS-C Engineering Unit (left) Being Tested in a Vacuum Chamber (right).

The HYDROS-C variant of the HYDROS system is a direct extension of the initial development work undertaken by TUI to produce a propulsion system sized for a 3U CubeSat. This work culminated in the production of multiple TRL-5 engineering units shown in Figure 1.These initial system design efforts provided innumerable insights into considerations for the design of the electrolyzer and propellant management subsystems as well as integration and packaging of a water electrolysis thruster. However, subsequent performance characterization by the Air Force Institute of Technology and TUI demonstrated subpar thruster performance (~0.5 N / ~250 s), likely attributable to combustion instabilities arising from sizing and geometry of the injector, chamber, and nozzle of the bipropellant microthruster.[1, 2] Based on the results of these characterization efforts and a subsequent refinement of the system requirements TUI is refining the HYDROS-C design for a demonstration as part of NASA's Pathfinder Technology Demonstrator mission. The new design, shown in Figure 2 with a 740 g capacity 'saddlebag' tank configuration, consists of a 0.8U thruster which can be integrated to a variety of tank configurations. Additional changes include improved electrolyzer and thruster subsystems, expanded propellant storage, and fully integrated avionics.

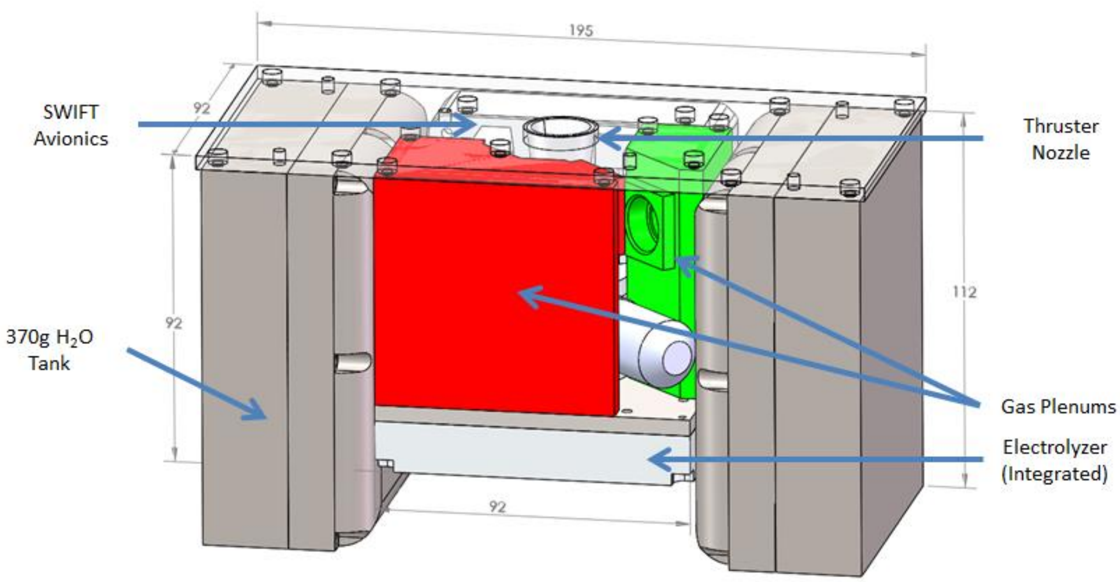


Figure 2. HYDROS-C Thruster with 740 g Capacity 'Saddlebag' Tank Configuration (mm).

In parallel with the development of the HYDROS-C for flight demonstration TUI has developed the HYDROS-M propulsion system to provide a bolt-on propulsion capability for MicroSat class spacecraft. Shown in Figure 3, the HYDROS-M system has increased propellant generation rates, propellant storage volume, and water capacity over the HYROS-C design, providing significant increases in total delivered ΔV and the capability to deliver that ΔV less time. The entire HYDROS-M system is capable of being encapsulated within a 381 mm diameter launch vehicle separation ring with an accompanying truncated 'propulsion cone' 81 mm in height with a 457.2 mm diameter base allowing it to be readily mated with existing small satellite buses. The HYDROS-M system has been selected as the primary propulsion system for a number of MicroSat missions. The HYDROS-M is in the process of being qualified for flight and delivery of TRL-8 units is anticipated in the second quarter of 2017.

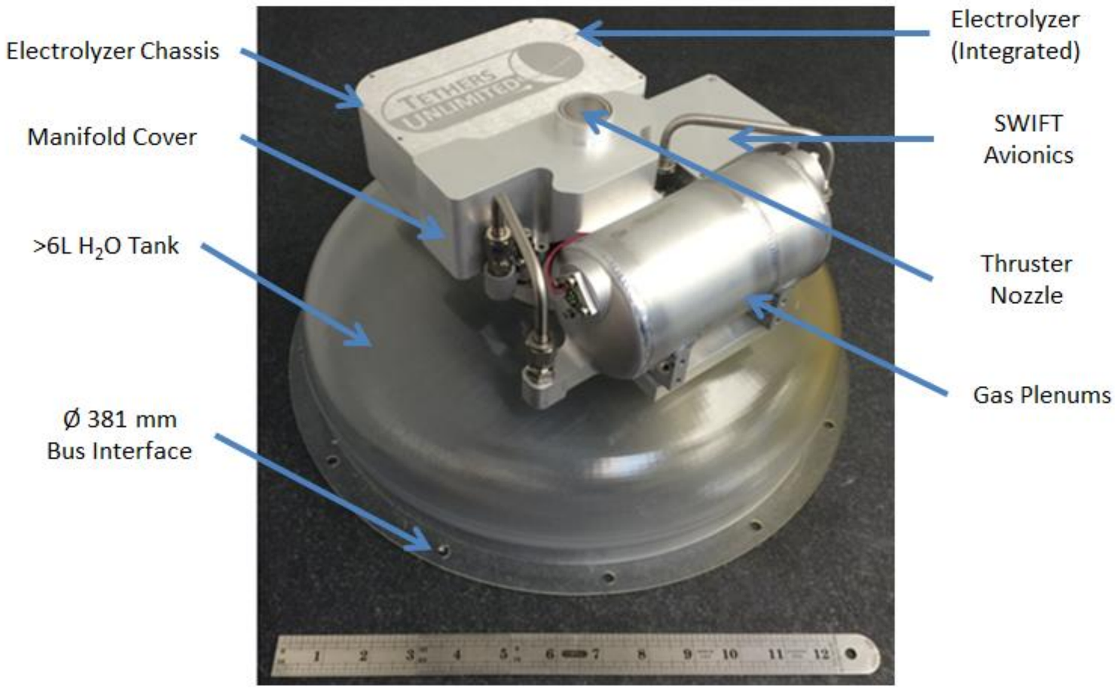


Figure 3. HYDROS-M Propulsion System.

The HYDROS-C and HYDROS-M systems share a common system architecture and development heritage highlighting the potential to adapt and scale the system to meet the wide range of mission CONOPS and propulsion requirements. In particular both systems are built around a common thruster subsystem allowing for thruster development and optimization efforts to serve both variants of the system. Further commonality is found in the reuse of multiple system components including an avionics architecture which leverages TUI's heritage SWIFT avionics hardware. Together the HYDROS-C and HYDROS-M systems provide a scalable set of propulsion capabilities for small satellite missions enabling a host of small satellite propulsion operations including:

- Rapid Orbital Maneuvering
- Life Extension / Drag Makeup
- High Performance Station Keeping/Formation Flying
- Momentum Wheel Desaturation
- Constellation Deployment and Maintenance

HYDROS PROPULSION SYSTEM ARCHITECTURE

The HYDROS thruster architecture, is composed of five principle subsystems: one or more water tank(s), a electrolyzer, a propellant management subsystem with integrated gas plenums, a bipropellant thruster and a SWIFT avionics subsystem. Water stored in the water tank(s) is deposited on demand onto the electrolyzer. With application of current, the water is electrolyzed by a microgravity compatible process at power efficiencies up to 88%.[3] Evolved hydrogen and oxygen gases are stored in separate gas volumes until they are mixed and combusted in the bipropellant thruster. Integrated avionics leveraging TUI's high-TRL SWIFT platform provide sensing and hardware control based on high level commands from a host flight computer via a defined high level command and telemetry interface.

The design and sizing of each of the principal components of the HYDROS architecture has direct impacts on the performance of the HYDROS propulsion system. Sizing of the electrolyzer and plenums, coupled with dynamic control of the consumed power, allows for tailoring of the system and CONOPs to meet a wide range of input power, impulse-bit, and thrust level requirements. Scaling of the HYDROS water tank allows the system to meet a wide range of mission ΔV requirements.

HYDROS Electrolyzer

The HYDROS electrolyzer electrolyzes deionized water into hydrogen and oxygen gases. Unlike common terrestrial electrolyzer designs, which operate by continuously pumping water through the electrolyzer, the HYDROS electrolyzer incorporates a microgravity-compliant water dispersion system into the electrolyzer feed design. Instead of relying on pumped water to transport the evolved gases and earth's gravity gradient is to separate the denser water from the less dense gases the HYDROS electrolyzer uses these passive design elements to ensure that water feed into the electrolyzer is utilized efficiently and does not intrude on downstream system elements. The HYDROS electrolyzer design allows for gas generation in zero gravity without the need for spinning the spacecraft or the use of excess water. The electrolyzer has been matured to TRL-6 through testing as part of the current integrated engineering unit and has been successfully demonstrated in both vacuum and gravity antagonistic environments. Propellant generation rates can be throttled by controlling the electrolyzer input power. Test results for the propellant generation rate as a function of input power for the HYDROS-M electrolyzer are shown in Figure 4.

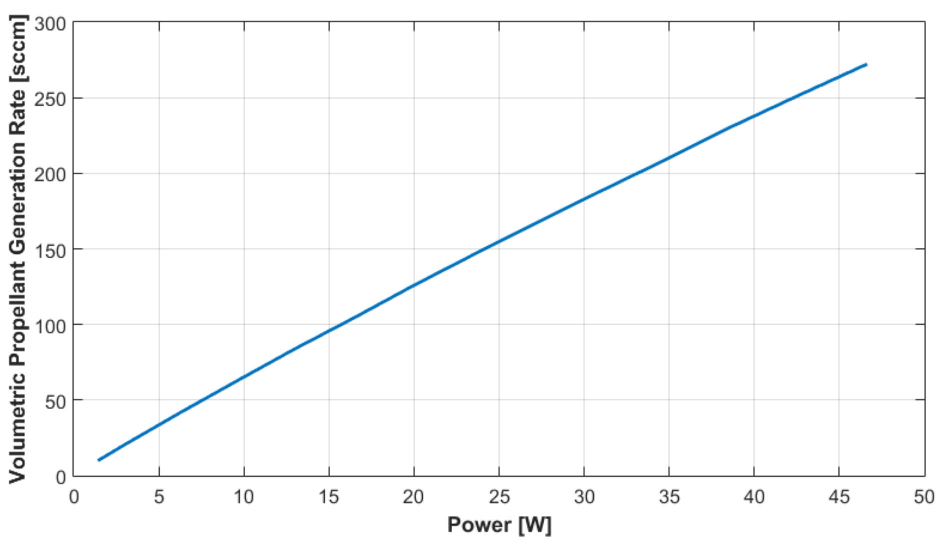


Figure 4. HYDROS-M Electrolyzer Performance Testing Results

Bipropellant Thruster

At the heart of the HYDROS system is a gaseous hydrogen and oxygen bipropellant thruster. The HYDROS-C and HYDROS-M systems share a common thruster design which can be used for both hot fires, where the propellant mixture is ignited through use of a commercial aerospace igniter, and cold gas firings with no ignition event.

The performance of the thruster was characterized in a vacuum chamber by directly measuring the force of the thruster during operation. The thruster and a representative propellant management subsystem were constructed in order to accurately represent the upstream conditions of the system. The thruster and a flight like injector with flight valves is mounted on the end of an arm in front of a load cell, firing the thruster produces force readings at the load cell directly proportional to the thrust. The thruster is fed either from a pair of external gas tanks or from an electrolyzer test fixture through a series of representative tubes and plenums. As with the flight system design the tubing and plenums are sized to provide a stoichiometric mass ratio of O_2:H_2 during a firing event of 8:1, matching the mass ratio of gases evolved from the electrolyzer. A pair of flight valves controls the flow into the combustion chamber. The valves are mounted as close to the combustion chamber as possible to reduce the excess volume of gasses to the combustion chamber. The system is monitored and controlled by a prototype avionics assembly, providing metrology and control through flight-like circuitry. Figure 5 shows the test assembly and all components setup inside the vacuum chamber.

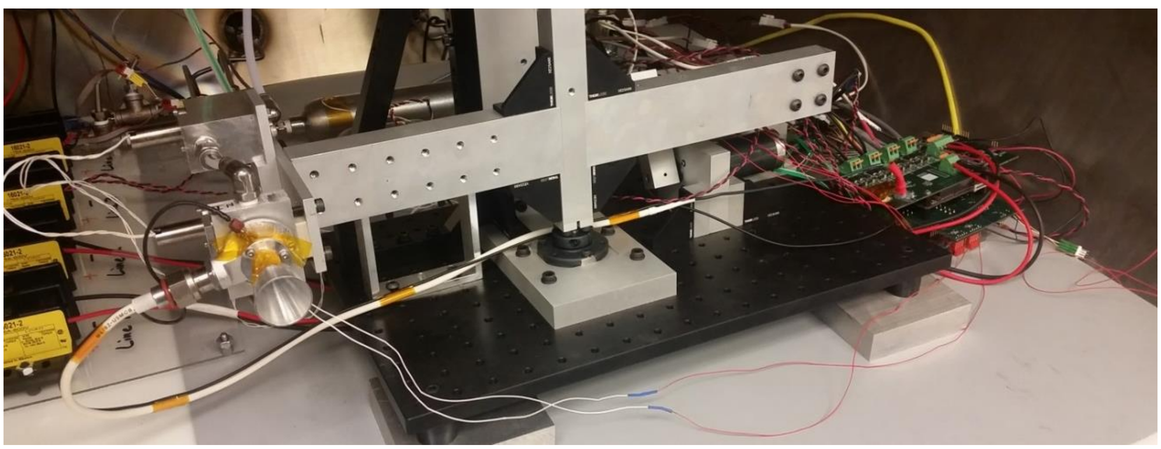
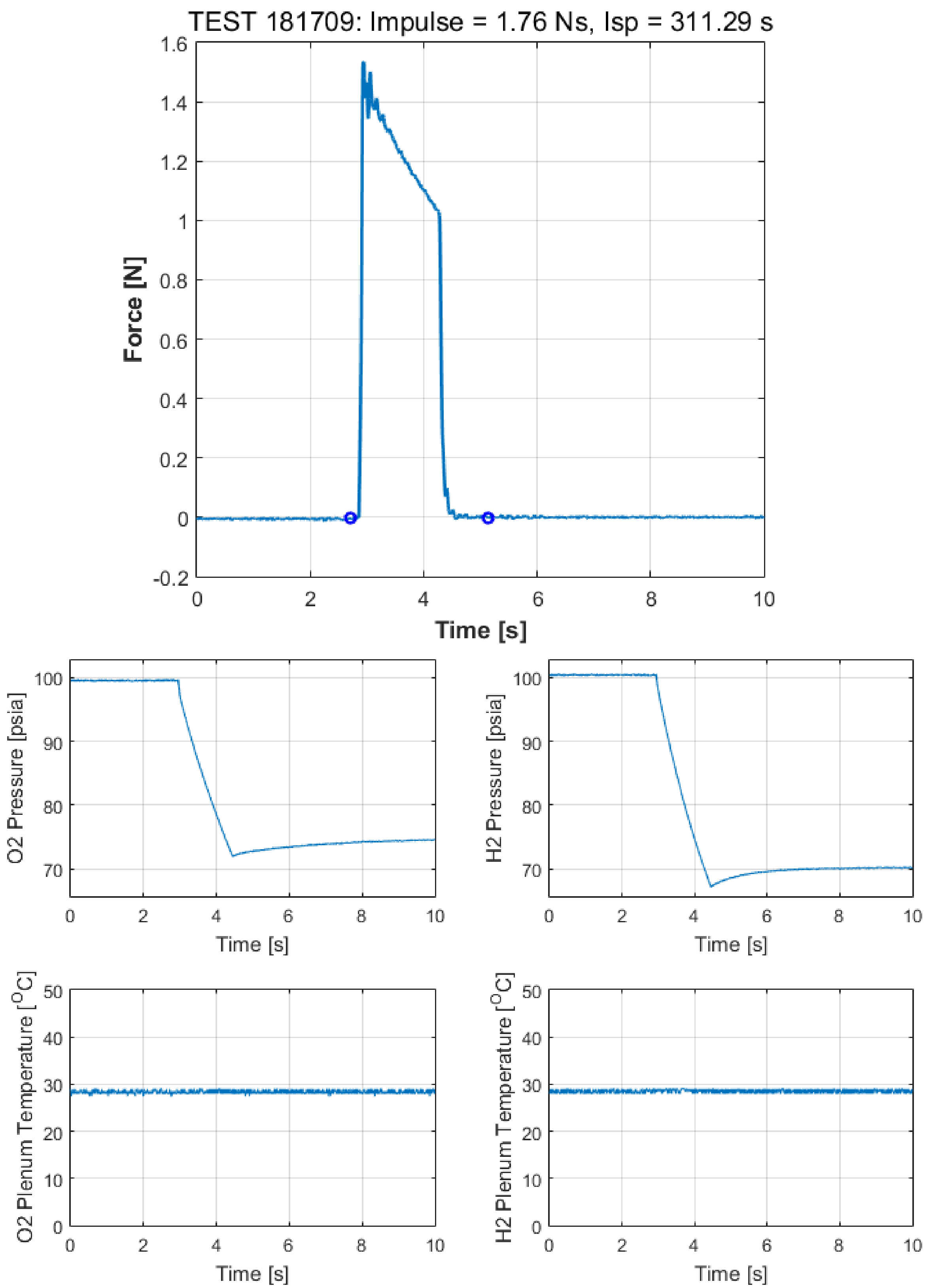


Figure 5. TUI's 3 m^3 Vacuum Chamber and HYDROS Thrust Stand

The performance of a thrust event is calculated by,

$$I_{sp} = \frac{I}{m_p g_0}, \tag{1}$$

where I is the impulse of the thrust event and m_p is the mass of propellant used to provide that impulse. The impulse is determined by integrating the thrust profile over the duration of the event and the propellant mass is determined by summing the differences between the species masses in the plenum and tube system, determined by the ideal gas law and knowing the temperature and pressure of the gasses. Figure 6 shows the thrust profile and system data from a representative 1.5 s thrust event.


TEST 181709: Impulse = 1.76 Ns, Isp = 311.29 s
Force [N]
Time [s]
O2 Pressure [psia]
H2 Pressure [psia]
O2 Plenum Temperature [^{O}C]
H2 Plenum Temperature [^{O}C]

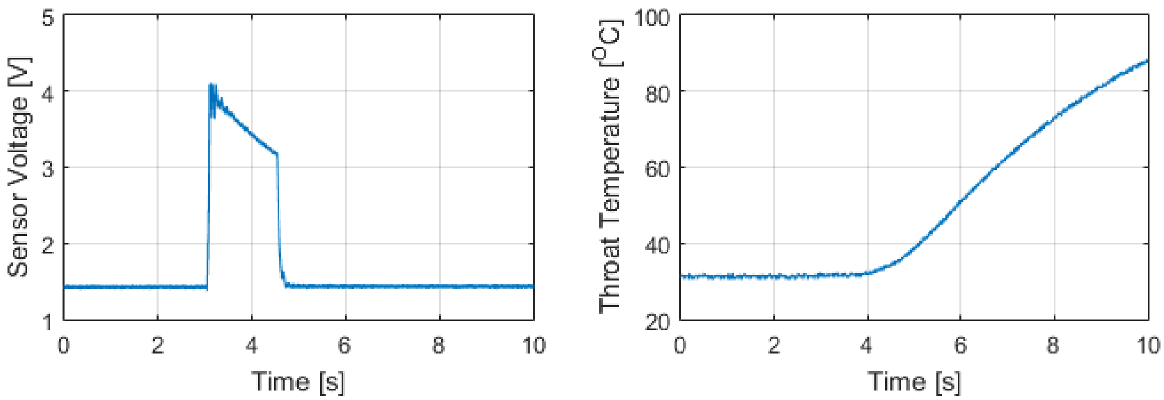


Figure 6. Representative Thrust Event Force Profile and System State

The thrust event shown in Figure 6 is representative of those collected to date. There is transient oscillation of the thrust stand which linked with successful ignition events that occurs for < 0.5 s and eventually dissipates. The decrease in thrust over the event duration is due to the reduction in upstream pressure of the system as the plenums blow down. For the specific event shown, integrating the force over time yields a total impulse of 1.84 Ns. For this event, there was a pressure drop in both plenums from 100 psia to ~73 psia yielding a propellant mass of ~0.60 mg. As shown on Figure 6, the specific impulse for this event is ~311 s, significantly better than other 'green propellant' chemical propulsion systems.

The HYDROS thruster is undergoing a continuing performance characterization test campaign to determine its performance over a wide range of operating conditions. However over the course of initial testing the average specific impulse has been demonstrated as 309.1 s ± 2.5 s. In addition to characterizing the performance of the thruster TUI is continuing to investigate changes to thruster geometry, material selection, injector design, and the ignition sequence to continue to improve performance. With more design and experimentation, we are hopeful to be able to deliver a thruster system with a specific impulse >350 s.

Avionics

Control of the HYDROS system is provided by a custom avionics subsystem developed in house by TUI leveraging our existing TRL-8 controller board and a HYDROS controller daughterboard. The avionics subsystem is capable of driving the electrolyzer with up to 40W of bus supplied power with precision voltage and current sense and control. The avionics also drive both the system valves and integrated heaters which provide thermal control of the system. Temperature and pressure sense is provided by flight qualified RTDs and pressure sensors. Host spacecraft interface is provided at a high level through a defined command and telemetry interface and a RS-422 or Ethernet physical interface.

HYDROS SYSTEM PERFORMANCE

The hybrid electrical/chemical nature of the HYDROS propulsion architecture leads to some unique system-level performance trades. At the most fundamental level, as with all propulsion systems, the total ΔV delivered by the system is dependent on the mass of fuel supplied by the system and the I_{sp} of the thrust events in which that fuel mass is consumed. Figure 7 and Figure 8 show how the total ΔV delivered by the baseline HYDROS-C and HYDROS-M thrusters scales as a function of propellant mass provided and host spacecraft mass. While Figure 8 shows two current point designs of the HYDROS propulsion system architecture the low operating pressure requirements and simple interfaces of the HYDROS water tanks makes them readily scalable to achieve desired total ΔV, as shown in Figure 7, with minimal effort.

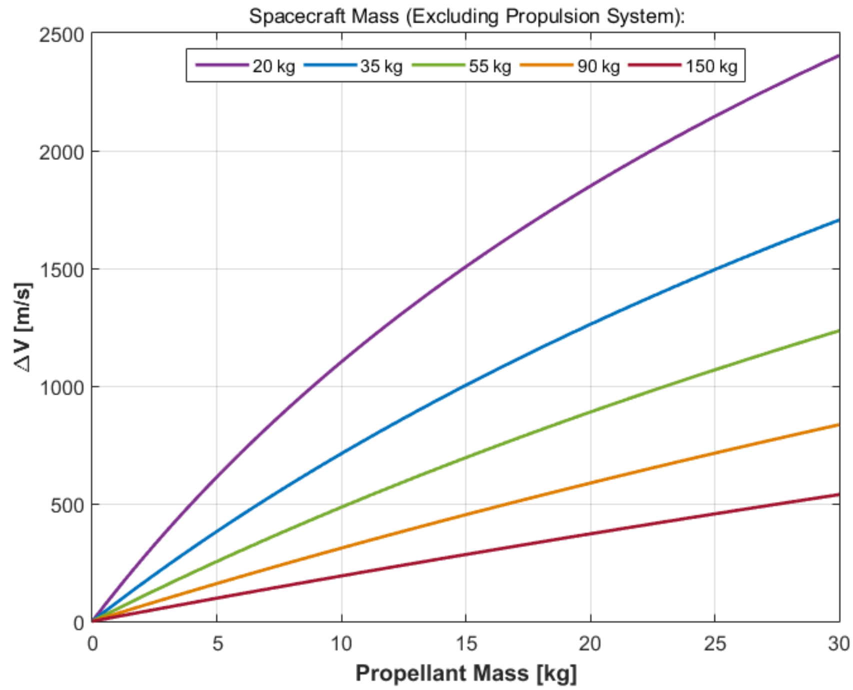


Figure 7. ΔV Delivered by HYDROS-C Thruster with Expanded Water Tank(s) Across a Range of Spacecraft Masses

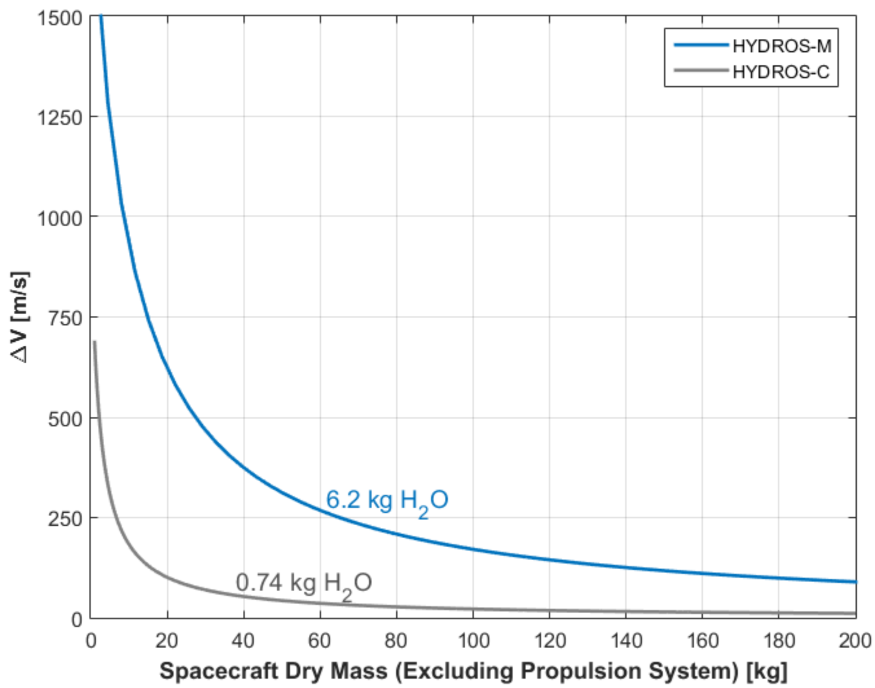


Figure 8. ΔV Delivered by the HYDROS-C and HYDROS-M Thruster Variants Across a Range of Spacecraft Masses

The uniqueness of the HYDROS propulsion system's performance trades lies with the *in-situ* generation of propellants inherent in the HYDROS architecture. As shown in Figure 4 the rate at which propellants are generated, and by extension the duty cycle at which the thruster is operated, is dependent on the electrolyzer sizing but highly throttalable by the electrolyzer input power. The propellant generation rate and the sizing of the gas plenums determines the minimum time between thrust events and the impulse capable of being imparted by each event. The minimum recharge time coupled with the performance of individual thrust events, like the one shown in Figure 6, can be used to consider the continuous operation of the system and determine the 'Effective Continuous Thrust' (ECT). This metric treats the HYDROS system as a thruster which is continuously operated at a lower thrust than is realized by any individual thrust event and provides a reasonable analogue to other electric propulsion systems. Since it is dependent on the propellant generation rate, the ECT of a HYDROS thruster is also throttalable by the supplied electrolyzer input power.

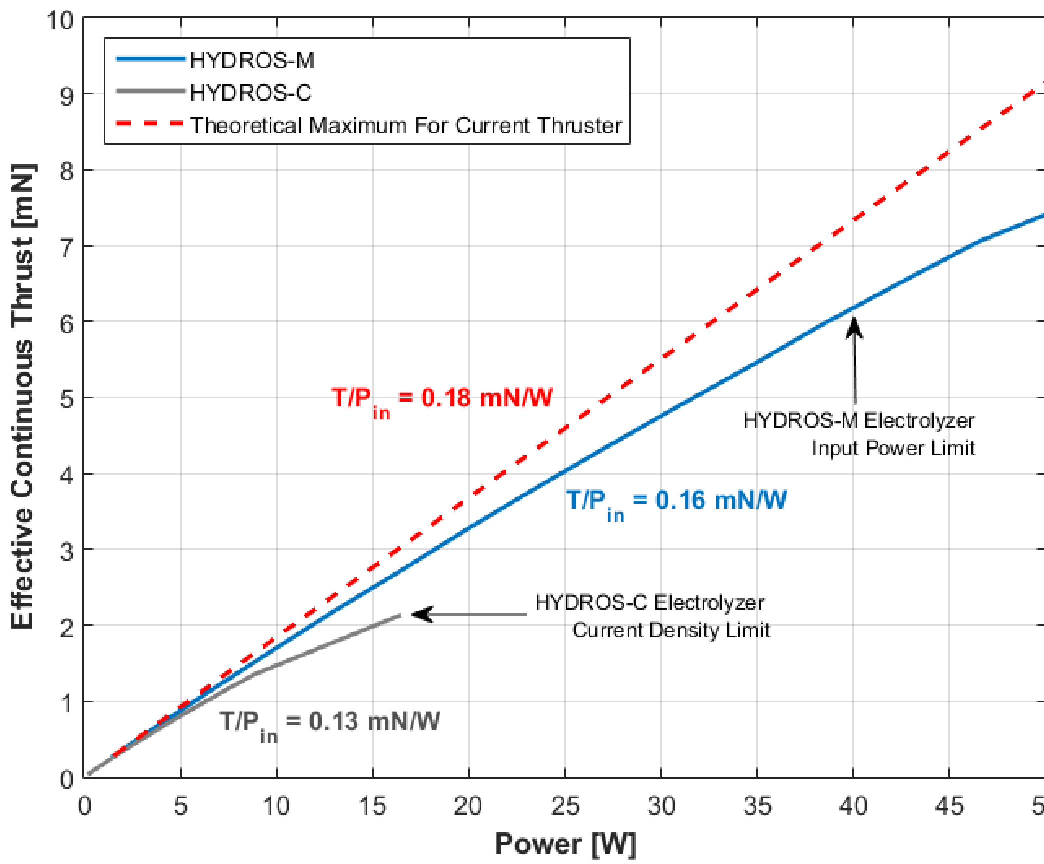


Figure 9. HYDROS Effective Continuous Thrust

Figure 9 shows the ECT vs power curves for the HYDROS-C and HYDROS-M systems. The ECT can also be used to readily show the theoretical maximum performance possible for a HYDROS propulsion system with a given thruster. This is achieved by considering the system performance given a perfectly efficient (or infinitely large) electrolyzer in which the voltage of the cell at all input current is 1.48 V, the thermoneutral potential for water electrolysis. Figure 9 shows the theoretical maximum performance of a HYDROS system using the current HYDROS thruster, as well as the ECT vs power curves for the HYDROS-M and HYDROS-C designs (current maximum input powers for the HYDROS-C and HYDROS-M units are 18W and 40W respectively). Taking the slope of the ECT vs power curve gives the thrust per power, a useful metric for preliminary sizing of the system. The HYDROS-M system has a thrust per power of 0.16mN/W which can be used to calculate the thruster efficiency via,

$$\eta_{thruster} = \frac{T_{ECT} I_{sp} g_0}{2P_{in}}, \tag{2}$$

where P_{in} is the power supplied to the system, and T_{ECT} is the ECT as defined above. Using Equation (2) the thruster efficiency of the HYDROS-M and HYDROS-C are determined to be 24% and 20% respectively, well aligned with state-of-the-art small electric propulsion systems.[4]

HYDROS-M Performance

Table 1 provides a summary of the performance of the HYDROS-M system. HYDROS-M was designed from the ground up to provide a bolt-on propulsion capability to MicroSat sized systems. As shown in Figure 8 HYDROS-M is capable of providing over 100 m/s of ΔV for systems in excess of 150 kg in mass. This capability coupled with an ECT of up to 6.8 mN enables HYDROS-M to provide significant orbit agility to highly capable spacecraft without imposing additional integration and launch considerations, risks, or costs.

Table 1. HYDROS-M Technical Performance Metrics

Metric	Value
Dry Mass	6.4 kg
Impulse per Thrust Event	1.75 Ns
Consumed Propellant Mass per Thrust Event	0.575 g
Isp	310 s
Average Thrust (Thrust Events)	1.2 N
Max Propellant Generation Rate	2.24 mg/s
Min Time to Refill Plenums	257 s
Water Capacity	6.2 kg
Max Effective Continuous Thrust	6.8 mN
Thruster Efficiency	24%
Total Number of Thrust Events	10,782
Total Impulse Delivered	18,869 Ns

HYDROS-C Performance

Table 2 highlights the technical performance metrics of the HYDROS-C system with the 740 g capacity ‘saddlebag’ configuration water tanks. While lacking the total ΔV and high end ECT performance of the HYDROS-M system the HYDROS-C thruster delivers the same per thrust event performance in a much smaller and more tightly integrated package. The potential for the HYDROS-C thruster to be integrated with larger water tanks at minimal cost and effort makes it viable propulsion solution for a wide range of potential applications.

Table 2. HYDROS-C Technical Performance Metrics

Metric	Value
Dry Mass	1.9 kg
Impulse per Thrust Event	1.75 Ns
Consumed Propellant Mass per Thrust Event	0.575 g
Isp	310 s

Average Thrust (Thrust Events)	1.2 N
Max Propellant Generation Rate	0.73 mg/s
Min Time to Refill Plenums	788 s
Water Capacity	0.74 kg
Max Effective Continuous Thrust	2.2 mN
Thruster Efficiency	20%
Total Number of Thrust Events	1,287
Total Impulse Delivered	2,252 Ns

CONCLUSION

HYDROS is a highly capable, green, hybrid-chemical/electric propulsion architecture. HYDROS delivers performance superior to alternative 'green propellant' chemical systems while maintaining thruster efficiencies comparable to existing electric propulsion systems.[5] TUI is currently developing two variants of the HYDROS system, HYDROS-C for CubeSat scale and larger applications and HYDROS-M for MicroSats. TUI has matured the HYDROS architecture to TRL-6 and anticipates delivering TRL-8 flight units in the second quarter of 2017.

ACKNOWLEDGMENTS

The authors would like to acknowledge support for development of the HYDROS thruster technology under NASA contracts NNX12CA09C and NNA16BD36C.

REFERENCES

[1] Liu, Y. 2016. "Performance Testing of Various Nozzle Designs for Water Electrolysis Thruster", *54th AIAA Aerospace Sciences Meeting*, AIAA SciTech Forum, (AIAA 2016-0954)

[2] James, K., et al. 2015 "Performance Characterization of the HYDROS™ Water Electrolysis Thruster." *Proceedings of the AIAA/USU Conference on Small Satellites*, Advanced Technologies III, SSC15-XI-5.

[3]Wrobel J W, et al., 2012 "PowerCube™ - Enhanced Power, Propulsion, and Pointing to Enable Agile, High Performance CubeSat Missions." *AIAA Space 2012 Proceedings*, *Pasadena, CA*.

[4]Conversano, R, et al., 2014 "Magnetically Shielded Miniature Hall Thruster: Performance Assessment and Status Update." *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference* (p. 3896).

[5]Powell, S., et al. 2016 "Experimental Evaluation of a Green Bi-Propellant Thruster for Small Satellite Applications." *Proceedings of the AIAA/USU Conference on Small Satellites*, SSC16-X-8.