

First End-to-End Technological Demonstration of a Water Electrolysis Hall Effect Thruster Operating with a Water Electrolyser

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The first end-to-end technological demonstration of a Hall Effect Thruster operating on the products of water electrolysis directly produced by a water electrolyser is presented. Here, the anode (thruster) consumes the oxygen while the cathode is fuelled by hydrogen, produced at the equivalent stoichiometric ratio. The complexity of operating on the potentially explosive ratios of oxygen and hydrogen required significant modifications of the vacuum facilities and the procedures which are typically used for inert propellants. This involved a careful pump selection, implementation of diverse purging systems, and refining the water electrolyser fluidics, all of which are detailed herein. The results of the test demonstrate the independent ignition capabilities of the cathode using hydrogen, and the operation of the entire system comprising the water electrolyser and the Hall Effect Thruster with the cathode. Notably, the gas wetness from the water electrolyser significantly influenced the discharge's stability, emphasising the necessity to fuel the anode and the cathode with dry gases for in-orbit technology demonstrations. It is estimated that the water electrolyser power consumption will only account for only 8% of the total system power considering the worst-case scenario, with the substantial majority of 83% potentially being accounted for by the thruster's anode discharge.

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I. Introduction

The landscape of space technology is experiencing a transformative phase with the evolution of Electric Propulsion (EP) systems, revealing their versatile utility across a diverse array of in-space applications [1]. These systems are now routinely utilised in orbit raising, Station Keeping (SK), End-of-Life (EoL) disposal, asteroid exploration, precise thrust control and interplanetary travel, EP has been employed in thousands of satellites to date [2].

Particularly, the maturation of EP has prompted its growing integration into multiple applications, including the rapidly growing adoption within Geostationary (GEO) communication satellites and the establishment of EP standards in Low Earth Orbit (LEO) megaconstellations composed of small satellites. EP systems are now progressively surfacing in satellites designed for navigation, Earth observation, missions in LEO and Very Low Earth Orbit (VLEO), as well as in scientific and robotic exploration missions [3–5].

At present, there is a paradigm shift underway with the emergence of numerous LEO small satellite constellations aiming to revolutionise high-speed and cost-effective internet communication services. Pioneering endeavours such as *SpaceX's Starlink* or *Airbus' OneWeb* have deployed thousands of satellites equipped with low-power (<1 kW) Hall Effect Thrusters (HETs) utilising argon/krypton/xenon for various orbital maneuvers and end-of-life operations, with many more to come [1]. Furthermore, the forthcoming iterations of these constellations envision larger satellites integrated with higher-powered EP systems. Not just for Earth orbiting applications but for interplanetary missions (such as the recent *NASA's Psyche* mission [6]), HETs have demonstrated a broad trade-space which allows them to satisfy a diverse set of mission requirements.

While the future prospects for EP appear promising, the substantial dependence of these satellites on their most prevalent propellant, krypton/xenon, presents a potential vulnerability in the future progression of this technology. Nowadays, this is mainly due to the susceptibility to price fluctuations and the scarcity of these propellants [7]. In the near future however, HETs aim to undertake deep-space missions integrating In-Situ-Resource-Utilisation (ISRU) for propellant acquisition from diverse celestial bodies [8, 9]. More than a mere cost problem, using noble gases for these purposes is not viable, as they cannot be found in significant quantities in the vicinity of the solar system. For these reasons, the imperative pursuit of a cost-effective, widely available propellant remains pivotal to secure a prosperous future for EP technologies, especially HETs.

Due to its cost-effectiveness, environmental friendliness, ubiquity on Earth and within the solar system, and its synergies with other spacecraft subsystems such as thermal cooling and life support systems for astronauts, water emerges as one of the most promising alternative propellants for forthcoming space missions employing HETs [7]. However, transitioning to the use of water as a HET propellant requires several non-trivial modifications, necessitating a comprehensive review of the fundamental physics and processes governing plasma generation and expulsion. Since the conceptualisation and divulgation of the idea, presented in 2018 and first published in 2019 [10], the Imperial Plasma Propulsion Laboratory (IPPL) has undertaken investigations into these phenomena, specifically focusing on two primary variants of water-fuelled technology: water vapour and water electrolysis.

The use of water vapour entails employing a heating and/or capillary system to convert liquid water into gas which directly feeds the anode. In such instances, the propellant for the cathode may also be water vapour if a radiofrequency cathode could be proven to successfully work in these conditions; otherwise, an alternative oxygen-free propellant must be utilised to prevent cathode contamination [11].

In the case of water electrolysis, a water electrolyser is placed aboard the spacecraft to split liquid water into two elements: oxygen (used as propellant for the anode) and hydrogen (acting as fuel for the cathode). It is important to note that an opposite arrangement (oxygen for the cathode and hydrogen for the anode) is unfeasible. Oxygen is highly poisonous to thermionic emitter cathodes, and in particular *LaB₆* cathodes, while also the hydrogen is too lightweight to generate any significant thrust plus being produced at only 1/8th the oxygen rate. In recent years, research at the IPPL has focused on experimentally optimising the geometry, magnetic field topology, and ceramic walls' material necessary for the anode of the HET to achieve the best possible performance [12–14] concurrently delving into the underlying physical phenomena [15]. Most recently the IPPL, together with partners *URA Thrusters Ltd.* and *Aliena Pte. Ltd.*, demonstrated successful operation of an anode and cathode fueled with oxygen and hydrogen from pressurised bottles. [16]. This article however, represents a significant advancement by presenting the first-ever end-to-end technological demonstration of a HET directly fed by a water electrolyser-generated products in a collaborative effort with the European Space Agency. Section II provides an overview of the hardware used and the setup devised for this experimentation. Section III details the outcomes derived from this technological achievement. Finally, Section IV summarises the work conducted to date and outlines the future prospects of this technology.

II. Methodology

A. Hardware

The hardware used for the technological demonstration is comprised of two different HETs designed for oxygen operation (throughout the text, referred to as the "anode"), a purpose build LaB_6 hollow cathode optimised for hydrogen operation, and a water electrolyser, representative of an engineering model designed for in-space applications.

1. Hall Effect Thrusters (Anode)



Fig. 1 Hall Effect Thrusters at the ESA Propulsion Laboratory of the European Space Agency. Left: Thruster *WET-HET* and cathode *Hydrocat*. Right: Thruster *AQUAHET* and the cathode *Hydrocat*. These devices are mounted on the Imperial Plasma Propulsion Laboratory thrust balance.

Two different HETs were used for the experimentation. The first one is "The Water ElecTrolysis Hall Effect Thruster" (referred to in previous work as the *WET-HET* [17]), property of Imperial College London. This thruster was specifically designed to run on oxygen while, at the same time, be flexible to accommodate different channel lengths and magnetic field profiles, to allow for experimental optimisation. The main goal was to identify a suitable combination that could achieve optimal thruster performance. A recap of the optimisation and final configuration of the thruster can be found in previous work [16]. The geometric configuration (channel length: 13 mm, width: 5 mm and mean diameter: 20 mm) and material selection ($BNSiO_2$ Grade M26 ceramic walls and stainless steel anode plate) which was presented there, is the one used throughout this technological demonstration.

The second thruster used is referred to as the *AQUAHET*, property of *URA Thrusters Ltd.* [18]. This is the second iteration of an oxygen-fuelled HET, built upon the lessons learnt from the experimentation with the *WET-HET*. The main difference between the two devices resides in the geometric configuration: the *AQUAHET* exhibits a larger mean diameter than the *WET-HET* (40 mm), thus operating at a higher mass flow. The channel length and channel width are kept the same as with the *WET-HET*, together with the material selection (ceramic walls and anode plate).

Both thrusters underwent individual testing alongside other hardware components (cathodes, water electrolyser, power supplies) to evaluate their distinct stabilities and suitability for comprehensive end-to-end water electrolysis testing from start to finish [12, 19, 20]. Figure 1 shows the two thrusters displayed at the European Space Agency (ESA) facilities while mounted at the Imperial College London thrust balance.

2. Cathode

The cathode used for the experimentation was provided by *Aliena Pte. Ltd.* It is a LaB_6 hollow cathode custom-designed specifically for hydrogen use, aptly named *Hydrocat* [21]. This cathode underwent prior testing at the IPPL facilities, employing hydrogen from pressurised containers in conjunction with the previously described thrusters [16]. This current study aims to assess the ignition capabilities of the cathode using hydrogen produced by a water electrolyser working independently in standalone mode, and also coupled with the thruster (anode). Figure 1 shows the cathode in conjunction with the thrusters used during the test.

3. Water Electrolyser

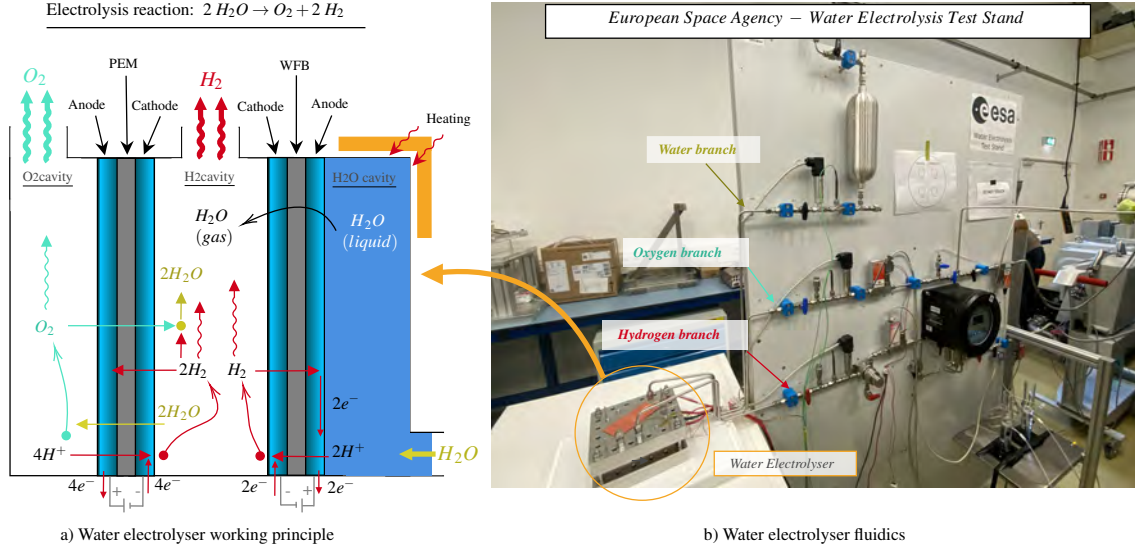


Fig. 2 Main schematic of the Cathode Vapour Feed (CVF) water electrolyser designed by the European Space Agency.

The water electrolyser [20] and its associated fluidic set-up [19] were developed by ESA. Readers are referred to the literature and previous work for a detailed description of these systems [19, 20, 22]. A summary is included hereafter.

The water electrolyser design is based on the "Cathode Vapour Feed" (CVF) topology shown in Figure 2. Within this submodel, water electrolyser are composed of two membranes: the Water-Feed Barrier (WFB) and the Proton-Exchange-Membrane (PEM), each one connected to an independent power supply with both connected to the same ground. This effectively segments the apparatus into three distinct cavities: the H_2O cavity (predominantly comprising liquid H_2O), the H_2 cavity (primarily consisting of gaseous H_2), and the O_2 cavity (largely composed of gaseous O_2). Upon initiating the system, liquid H_2O heated up to a certain temperature (for example, 70 °C) permeates the WFB, transitioning into gaseous H_2O . Subsequently, gaseous H_2O diffuses through the PEM, undergoing decomposition in accordance with the fundamental water electrolysis reaction: $2H_2O \rightarrow O_2 + 2H_2$. Notice that this reaction is the result of the Oxygen Evolution Reaction (OER), half of the main electrolysis reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ and the second half, the Hydrogen Evolution Reaction (HER): $2H^+ + 2e^- \rightarrow H_2$. These reactions occur simultaneously to close the electrical circuit. The polymeric membrane functions as an electrolyser, facilitating the migration of protons through the electric field. It is noteworthy that these reactions are enabled by a catalyst applied to the membrane, which is made up of iridium oxide on the oxygen side and platinum on the hydrogen side. A schematic of the CVF, which also highlights additional reactions occurring within the device, is included in Figure 2a. For instance, within the H_2 -cavity, H_2 may diffuse through the WFB, transforming into $2H^+$, which then diffuses back to the H_2 cavity. H_2 can also permeate through the PEM towards the O_2 cavity, where $4H^+$ can traverse back through the PEM, get neutralised by the electrons in the circuit and reform into $2H_2$ in the H_2 cavity. Additionally, O_2 has the capacity to diffuse through the PEM, subsequently recombining with the $2H_2$ in the H_2 cavity to generate $2H_2O$. This resultant compound can once again permeate through the PEM, reinitiating the primary electrolysis reaction. Ultimately, the permeability of water across both membranes dictates that both the hydrogen and oxygen produced contain varying amounts of water vapour. Understanding the impact which the presence of this water vapour has on the thruster and the cathode operation is critical for the proposed application. The inclusion of these effects separates this study from previous experiments, which all used high purity dry gases supplied from cylinders.

Still CVF electrolyser outperform other concepts such as the Liquid-Anode-Feed (LAF) electrolyser thanks to its improved behaviour in microgravity conditions. This is because LAF electrolyser rely on the density contrast between fluids for their separation from liquid water.

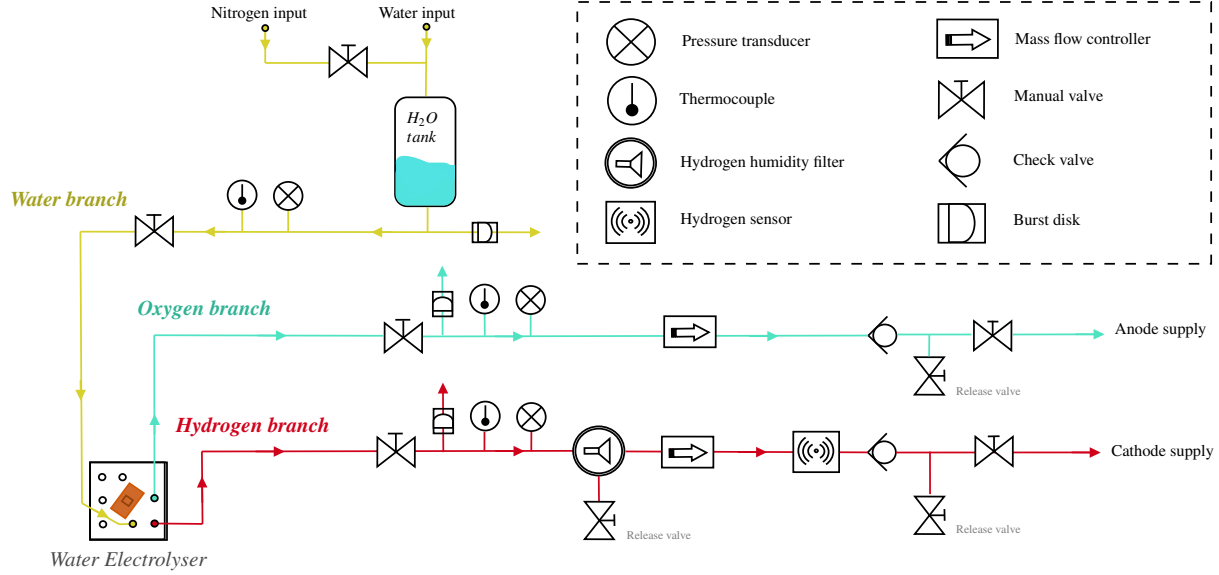


Fig. 3 Water electrolyser fluidics schematic set-up for testing at the ESA Propulsion Laboratory of the European Space Agency.

Although LAF electrolyser produce greater current density than CVF electrolyser because they are fed with liquid water instead of vapour, in the absence of gravity to facilitate this separation, LAF electrolyser encounter operational challenges [20].

The water electrolyser is arranged together with the fluidics as shown in Figure 2b. A more detailed schematic of the different parts composing the water electrolyser fluidics system is shown in Figure 3.

The propellant feed system is composed of three different branches: the water branch, which provides liquid water to the electrolyser, and the oxygen and hydrogen branches, as outputs from the water electrolyser.

To start with, liquid water is fed into the system. A nitrogen feed is also available in order to pressurise water within the tank, to achieve a more realistic scenario in a space mission. The temperature and pressure of the output feed of the tank are monitored using pressure transducers and thermocouples. A burst disk is also employed to relieve the fluid in case the maximum allowed pressure is exceed within the line (between 40-50 bars at 20 °C, 293K). A manual valve allows liquid water to flow into the water electrolyser, which transforms liquid water into gaseous oxygen and hydrogen as explained above. Manual valves are positioned at the start of both the oxygen and hydrogen lines. Subsequently, temperature and pressure sensors, along with burst disks, are installed for each line. The hydrogen line is additionally equipped with a hydrogen humidity filter designed to partially capture the moisture present within the line. The water content contained within the hydrogen can be released via a manual valve. To regulate the oxygen and hydrogen mass flow, mass flow controllers are then employed. Following this, a hydrogen sensor is incorporated to assess the purity of hydrogen within the pipeline. Check valves are implemented to ensure unidirectional fluid flow, for both lines. Additionally, two manual valves are configured to purge oxygen and hydrogen if required (see Figure 3). Finally, two manual valves allow the flow into the thruster (anode) and the cathode.

B. Facilities and Set-Up

The experiments conducted were performed within the Small Plasma Facility (SPF) of the ESA Propulsion Laboratory (EPL), property of ESA. This test, contrary to other experiments using noble gases, required a modified set-up of the vacuum chambers to safely store and provide oxygen and hydrogen at stoichiometric ratios. The comprehensive layout of the facilities and diverse components for end-to-end testing is shown in Figure 4. The different elements enumerated in this diagram are shown in Table 1. This final configuration incorporates all the insights gained from prior experiments conducted at the IPPL (at Imperial College London) [12, 16].

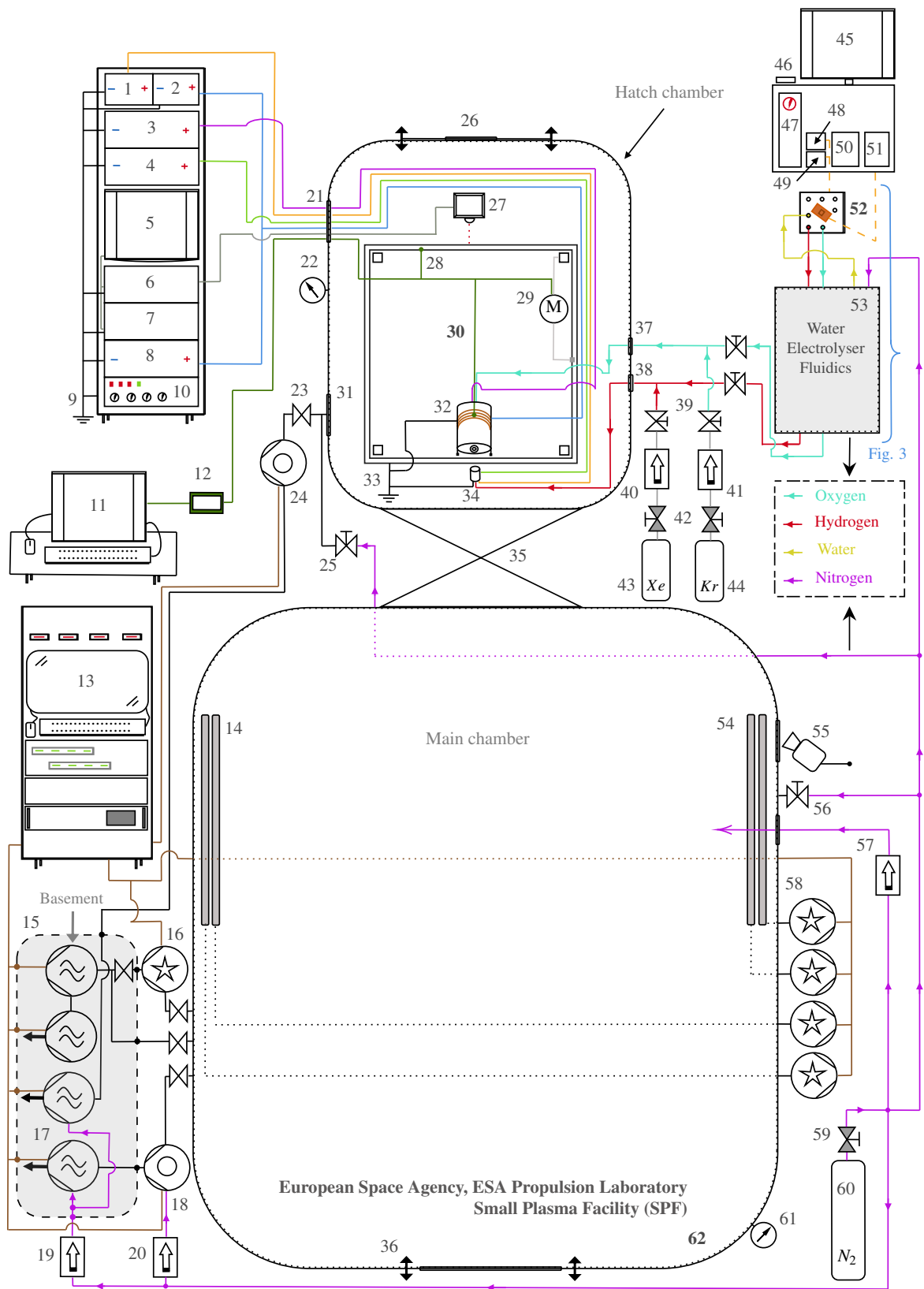


Fig. 4 Main schematics of the water electrolysis electric space propulsion testing at the ESA Propulsion Laboratory of the European Space Agency. The Small Plasma Facility vacuum chamber was used for the experimentation.

Table 1 Description of the elements depicted in Figure 4.

1 Heater power supply (Agilent 6038A: 0-60V, 0-10A)	32 Water ElecTrollysis Hall Effect Thruster (anode)
2 Inner electromagnet power supply (Agilent 6038A: 0-60V, 0-10A)	33 Grounding connection (same as 9)
3 Anode power supply (FUG MCP 4200-650: 0-650V, 0-6A)	34 Cathode (Hydrocat)
4 Keeper power supply (Glassman LPD 600-10: 0-600V, 0-10A)	35 Main gate valve (hatch to main chamber)
5 Thrust balance monitor	36 Door (main chamber)
6 Thrust balance electronics box	37 Vacuum feedline (oxygen)
7 Thrust balance computer	38 Vacuum feedline (hydrogen)
8 Outer electromagnet power supply (Delta SM120-25D: 0-120V, 0-25A)	39 Manual valves set
9 Power supplies ground connection (same as 33)	40 Mass flow controller (xenon)
10 Auxiliary power outlet	41 Mass flow controller (krypton)
11 External computer station and monitor	42 Pressure regulators (xenon and krypton)
12 Thermocouples electronics	43 Cathode propellant bottle (xenon)
13 Pumping system control station	44 Anode propellant bottle (krypton)
14 Cryo panel (x2, not used)	45 Monitor (electrolyser control station)
15 Basement	46 Analogue to digital converter (ADC, SCB-68A)
16 Cryo pump, with compressor (COOLVAC 10 000 CL)	47 Switchbox
17 Roughing pump (Varian TriScroll 300 Dry Scroll Pump)	48 Electrolysis membrane power supply
18 Turbopump (VARIAN Turbo-V 3K-G ISO 250 F)	49 Water feed barrier power supply
19 Mass flow controller, roughing pump purging (nitrogen)	50 PXI controller
20 Mass flow controller, turbopump purging (nitrogen)	51 Pressure transducers power supply
21 Vacuum feedthrough (power)	52 Water electrolyser
22 Pressure gauge (hatch chamber)	53 Water electrolyser fluidics (refer to Figure 3)
23 Gate valve	54 Cryo panel (x2, not used)
24 Turbopump (Leybold, TURBOVAC 1000 C)	55 Camera
25 Venting valve (hatch chamber)	56 Venting valve (main chamber)
26 Door (hatch)	57 Mass flow controller, chamber purging (nitrogen)
27 Laser ILD1750	58 Cryo heads (x4, Leybold COOLPOWER 140T)
28 Thermocouple (to thrust balance)	59 Pressure regulator (nitrogen)
29 Servomotor (for calibration)	60 Purging and venting propellant bottle (nitrogen)
30 Thrust balance	61 Pressure gauge (main chamber)
31 Vacuum feedthrough	62 Small Plasma Facility (European Space Agency)

The hatch chamber measures 1.0 m in length and diameter, while the main chamber has dimensions of 3.35 m in length and 2.0 m in diameter. The thrust balance [23] is positioned within the hatch chamber, strategically situating the system's thruster and cathode at the gate valve's periphery between the hatch and the main chamber. In this way, the plasma is free to expand into the main chamber where the reflection of the plasma and neutrals is reduced by the large vacuum volume.

Notice that, in this first test, safety was the most important aspect to consider. The mixing of oxygen and hydrogen at stoichiometric ratios, even in small amounts, could end up in ignition unless adequate precautions are taken. This experimentation, marking ESA's first-ever test involving the mixing of these gases for EP, necessitated a careful safety assessment to ensure maximal safety despite imposing potentially more challenging conditions for the thrusters.

For that reason, within the set-up, krypton and xenon bottles with their respective mass flow meters are also set in place to initially feed the thruster (anode) and cathode. In that way, once the system has successfully been ignited, the amount of noble gases into the system is slowly decreased while the oxygen and hydrogen flow from the water electrolyser increases; until only oxygen and hydrogen are used to feed the system. This gradual transition is much safer as it permits monitoring the safety of the set-up with progressive increments of oxygen and hydrogen, while avoiding any potential initial sparking of the thruster and cathode (*i.e.*, preserving the integrity of the system for a longer time duration). Notice that, although this transition was implemented in this laboratory test, it is not needed (nor recommended) for an in-orbit space demonstration.

The initial pumping stage consisted of two roughing pumps (model *Varian TriScroll 300 Dry Scroll Pump*, element 17): one designated for the main chamber and an additional pump allocated to the hatch chamber. Two extra roughing pumps, positioned at the exit of the cryo pump, were available. However, as will be explained later, due to the non-usage of the cryo pump, its associated primary pumps remained inactive. The gas ballast system of the two primary pumps was fed with nitrogen during the test campaign. This approach was recommended for the purposes of diluting the oxygen and hydrogen, requiring a continuous nitrogen flow of 10 L/min.

However, these pumps were situated within the non-ventilated basement of the facility, as depicted in Figure 4 (element 15). Venting the gases from the facility into the non-ventilated basement raised safety concerns due to the

potential reduction of oxygen levels below the safety threshold (19% or below). Following this concern, it was calculated that, due to the large volumetric area of the basement, even after 20 hours of testing with the purging system active and the two pumps in operation, the oxygen level in the basement would remain higher (20.2%) than the minimum required level (19%) mandated by the health and safety department of the European Space Agency. Consequently, the purging system was activated, which permitted the use of these pumps.

The second pumping stage was composed of two turbopumps: a *Leybold, TURBOVAC 1000 C* for the hatch chamber (element 24) and a *VARIAN Turbo-V 3K-G ISO 250 F* for the main chamber (element 18). To prevent potential back flow of contaminant into the bearing area, the main chamber turbo pump is designed to operate with inert purge gas flow from the upper bearing area to the foreline. For the purposes of these tests, nitrogen is selected as the purge gas (with the recommended 20 sccm flow used) to further reduce the risk of ignition. Notice however that only the turbopump connected to the main chamber had nitrogen purging capability. Therefore, the turbopump for the hatch chamber was solely used for the initial evacuation of the facility and remained disconnected thereafter, while the turbopump for the main chamber and its purging system were used throughout all experiments.

The third stage included a cryo pump (element 16) and four cryo panels (elements 14 and 54). However, for this initial test, the third stage could not be used as the equipment had never been tested under these conditions, nor had the facilities previously operated with both oxygen and hydrogen simultaneously. Concerns arose regarding potential oxygen and hydrogen accumulation at the cryo pump, posing considerable risks during its regeneration process if both gases were released simultaneously. Furthermore, there were concerns that the cryo panels might be compromised upon contact with oxygen. Therefore, they were covered and not used throughout the test.

In order to further minimise any potential risk of ignition, nitrogen was added to the chamber during testing. The goal was to replicate the ratios of oxygen and nitrogen present in atmospheric air ($N_2 \approx 78\%$, $O_2 \approx 21\%$). For instance, if 1.6 mg/s of oxygen was introduced, 5.9 mg/s of nitrogen was simultaneously injected into the chamber.

Note that, in contrast to the previous experimental setup [16], oxygen and hydrogen do not come from pressurised cylinders: the gases are produced by the water electrolyser. Therefore, safety concerns regarding the presence of large volumes of pressurised oxygen and hydrogen in proximity are not applicable, and both gases can co-exist outside and inside the vacuum chambers.

Lastly, in terms of electrical connections, the bottom parts of the thrust balance and hatch and main chambers are set to ground (element 33), which is the same ground as the power supplies (element 9). The central moving platform of the thrust balance is floating [12, 23]. The electronics to power the HETs including the cathode are listed in Table 1. Notice that the thruster *AQUAHET* requires two power supplies to activate its electromagnets (inner and outer electromagnets, elements 2 and 8) whereas the *WET-HET* only needs one (inner electromagnet, element 2).

Following the successful completion of this test campaign, a number of possible facility enhancements for subsequent tests were identified. These are detailed in Section IV.

III. Technology Validation Results

The electrolyser and the cathode were independently validated, followed by an entire end-to-end system validation. Section III.A provides an in-depth analysis of the characterization of the water electrolyser. Section III.B summarises the results of the cathode fuelled by hydrogen coming from the water electrolyser. Finally, Section III.C encapsulates the system's validation encompassing the water electrolyser coupled with the HET and the cathode.

A. Water Electrolyser

The operational characteristics of the water electrolyser are significantly influenced by its temperature. Previous research has outlined the correlation between the water electrolyser's mass flow production rate, characterised by the current-voltage (IV) curve, and the temperature [20]. The maximum continuous mass flow production without compromising membrane integrity (1.3 mg/s), was achieved at 70 °C. To attain this temperature, two heaters positioned at the top and bottom of the water electrolyser are used, consuming a combined maximum power of 175 W. This large heating capacity serves to accelerate the heating process of the electrolyser. The current design, featuring two large clamping plates with substantial heat capacity, has not been fine-tuned to minimize power requirements [20]. Altering materials or redesigning the electrolyser could significantly reduce the necessary heating power. It is also worth pointing out that this heating capacity of 175 W is employed to increase the temperature of the electrolyser to its nominal level. Once this temperature is reached, the heating power required to maintain the nominal temperature decreases. Nevertheless, to ensure a conservative estimate, this heating power is used for calculating the overall power demands of the system. As will be explained in Section III.C, even with a suboptimal design and being conservative, the

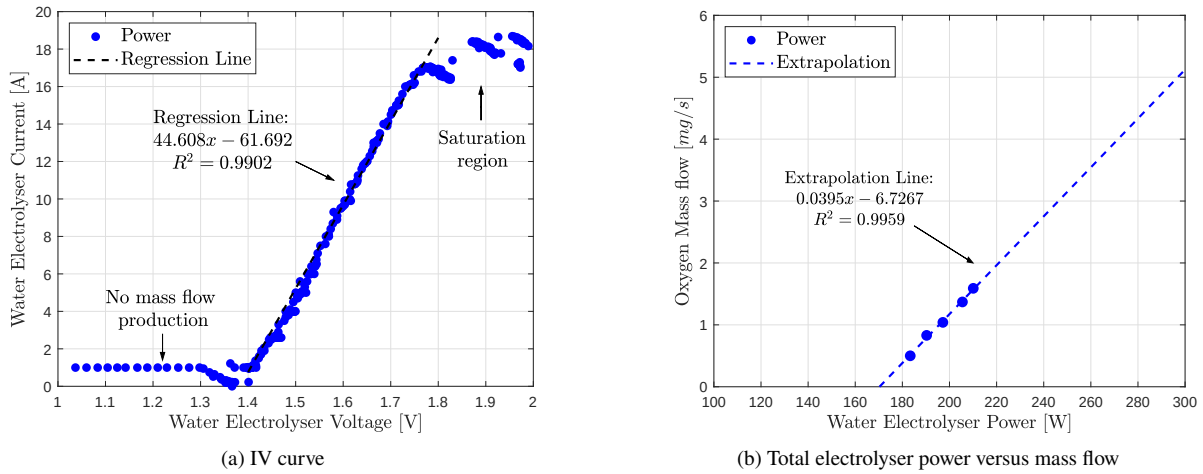


Fig. 5 Water electrolyser characterisation: a) current-voltage (IV) curve, and b) total electrolyser power versus oxygen mass flow.

water electrolyser's total power consumption represents a fraction (8%) of the system's overall power, primarily dictated by the thruster's discharge power (83%).

Figure 5a shows the IV curve corresponding to the water electrolyser at 70 °C. Three distinct regions are discernible. Below 1.4 V, the water electrolyser exhibits negligible to none mass flow production, with currents measuring below 1 A. Within the range of 1.4 – 1.8 V, a linear relationship is observed, resulting in varying mass flow rates before reaching saturation (third region). Each point on the IV curve corresponds to a different power setting, with higher power correlating to increased mass flow production. Figure 5b shows the total power consumption of the water electrolyser against the oxygen mass flow. Notice that the oxygen to hydrogen mass flow production, in stoichiometric ratio, is hydrogen-to-oxygen (Φ) = 1:8. In other words, for each gram of hydrogen produced, 8 grams of oxygen are created. This is due to the differences in molecular weight between oxygen ($O_2 = 16$ amu) and hydrogen ($H_2 = 2$ amu). The maximum hydrogen and oxygen mass flow rates that this water electrolyser can produce are 0.2 mg/s and 1.6 mg/s, respectively. The power required to achieve this condition is 211 W. As explained in Section II.A.3 and shown in Figure 2a, power is needed for the two membranes and to heat up the device. Specifically, 35 W are needed to power the PEM (first membrane) and 1 W for the WFB (second membrane). The rest of the power (175 W) is required for sustaining a consistent temperature of 70 °C.

Consequently, in the current configuration, heating constitutes the majority of the total power prerequisite for the water electrolyser to operate.

A linear projection of the power/mass flow relationship suggests that a HET requiring ~ 5.0 mg/s of oxygen (anode) and ~ 0.6 mg/s of hydrogen (cathode) would demand a water electrolyser consuming ~ 300 W of power.

B. Hydrogen Cathode

This section compiles the results obtained during the standalone validation of the cathode *Hydrocat*, provided by *Aliena Pte. Ltd.*, directly fuelled by hydrogen produced by the water electrolyser.

As highlighted in Section II.B, in order to maximise safety and to better preserve the hardware for future tests, the ignition is first achieved with a noble gas (in this case xenon). Then, hydrogen is progressively introduced into the system. The transition from xenon to hydrogen and the consequent alteration in plume colour are visually depicted in Figure 6. Moreover, Figure 7a illustrates the set and measured mass flows of xenon and hydrogen during the validation test. The cathode's condition and facility status were continuously monitored to ensure overall safety and hardware integrity. Stable operation with hydrogen was achieved, allowing successful testing across a range of hydrogen mass flows spanning 0.07 – 0.16 mg/s, with the cathode operating uninterrupted for over 15 minutes before the test conclusion.

Throughout this test, the cathode keeper discharge when using either xenon or hydrogen was recorded (Figure 7b). From the results, it is possible to observe how the mass flow rates using hydrogen are lower than the ones of xenon.

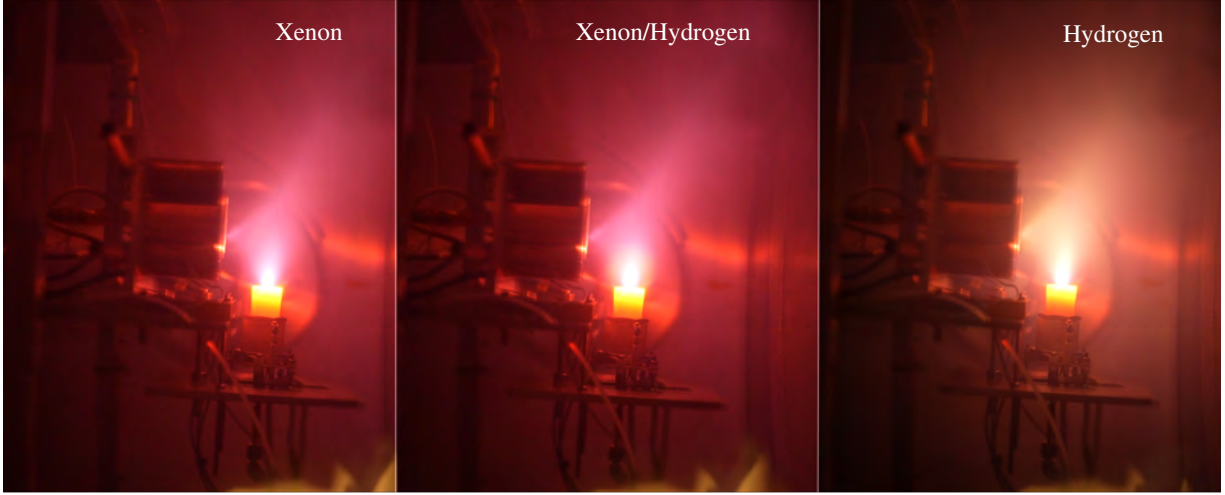


Fig. 6 Transition of *Hydrocat* operation from only xenon to only hydrogen during standalone testing.

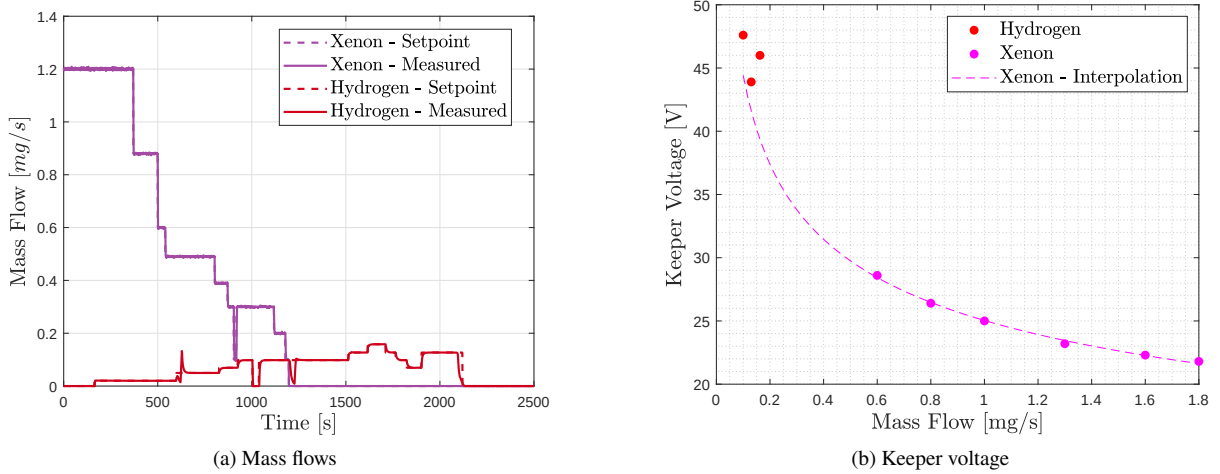


Fig. 7 *Hydrocat* cathode validation: a) transition of mass flows used from xenon to hydrogen, used during the experimental validation, and b) keeper voltage as a function of either the xenon or hydrogen mass flows.

This is a consequence of the inherent limitation of the water electrolyser to produce larger mass flows, and hydrogen being limited to the stoichiometric mass ratio production ($\Phi = 1:8$). Consequently, due to the lower mass flow rates, the recorded keeper voltage with hydrogen surpassed the one with xenon, elevating the total power consumption of the cathode.

However, even with these varying mass flow rates of hydrogen and xenon, the discrepancy in keeper power is marginal as a percentage of the total system power (~ 96 W for hydrogen at 0.16 mg/s and ~ 56 W for xenon at 0.6 mg/s). A visual examination of the power function interpolation with xenon (displayed in Figure 7b) indicates that the power consumption difference at equal mass flow rates between these two propellants would be even more negligible.

C. End-to-End Water Electrolysis Hall Effect Thruster Testing

In this section, the results of the end-to-end testing of the HET and cathode fuelled by oxygen and hydrogen, respectively, directly produced by the water electrolyser fed by liquid water, are presented. Figure 8a shows the set and measured flows of the system during the test. Figure 8b displays the background pressures recorded at the same time these mass flows were introduced into the system.

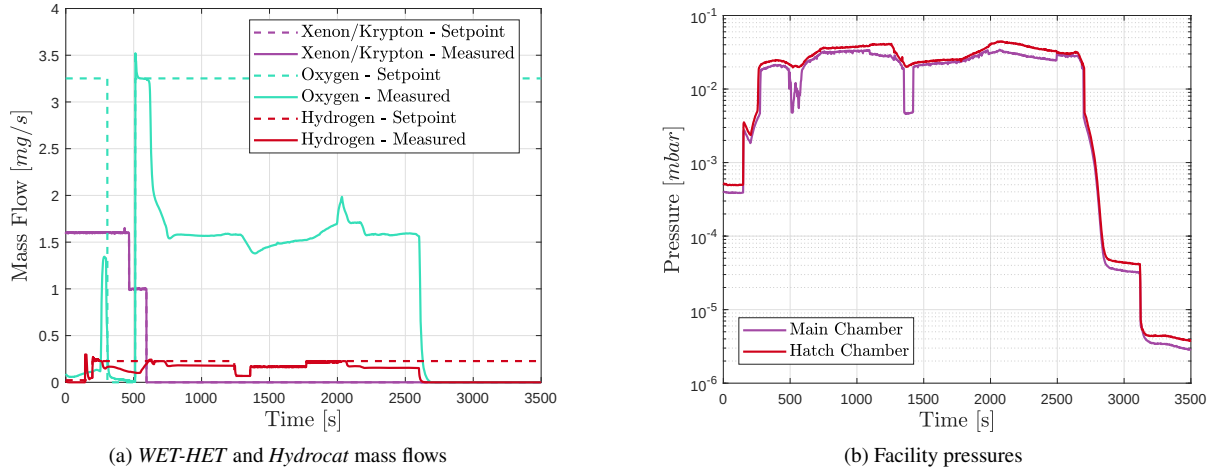


Fig. 8 End-to-end water electrolysis propulsion validation: a) mass flows used by the oxygen-fuelled thruster *WET-HET* and hydrogen-fuelled cathode *Hydrocat*, and b) facility background pressure during the test.

In a similar fashion to the standalone cathode test (Section III.B), the thruster (anode) and cathode are first ignited with krypton and xenon respectively. The *WET-HET* thruster and *Hydrocat* cathode can be seen operating with these gases in Figure 9.

Once ignition and stable operation with xenon/krypton was established (at time $T = 0$ s in Figure 8a), the gradual introduction of oxygen and hydrogen into the system commenced. Continuous monitoring of the facilities and the system ensued to ensure discharge safety and stability. Notably, during the initial transition phase, the thruster operated at a higher mass flow rate (~ 3.2 mg/s) than the steady-state capacity of the electrolyser. This was achieved by pressurising a section of the line with the oxygen generated by the water electrolyser. This methodology (referred to as “gas puff” [12, 16]) ensured the initial stability of the thruster (anode) before reaching the steady-state conditions of pure water electrolysis feed (~ 1.6 mg/s of oxygen for the anode and ~ 0.2 mg/s for the cathode) at time $T = 750$ s.

At that point, various oxygen and hydrogen mass flows were introduced into the thruster (anode) and cathode to evaluate the system’s stability range. The thruster (anode) successfully operated on oxygen within the range of 1.3 – 3.2 mg/s, while the cathode functioned optimally with hydrogen in the range of 0.07 – 0.22 mg/s. The total duration of this test was ~ 34 minutes. To complement the validation phase, the mass flow setpoints of oxygen and hydrogen were set to the highest value (fully open valve configuration) during the steady firing so that the flow was not restricted from the mass flow meters and the gas production of the water electrolyser was fed into the system.

During the tests, facility pressure measurements in both the main and hatch chambers were concurrently recorded (Figure 8b). Notably, the background pressures observed during the test were unusually high. As explained in Section II.B, due to concerns about mixing oxygen and hydrogen at stoichiometric ratios, a portion of the pumping system was inactive during this technological validation test (i.e., with the turbopump of the hatch chamber, cro pumps and cryo pannel being inactive). It is worth mentioning however, that the pressure gauges are calibrated for measuring vacuum environments with nitrogen, so the background pressures recorded might be slightly overestimated.

Another significant factor impacting the system discharge relates to the humidity content within the feedline. As elaborated in Section II.A.3, CVF water electrolyzers produce a humid compound of oxygen and hydrogen, rather than dry gases. In space hardware, desiccants could be employed to dehydrate gases from water electrolyzers. However, this initial test aimed to evaluate the system’s response without desiccants to assess their importance for future water electrolyser advancements. As depicted in Figure 9, the line’s humidity content caused a variation in the thruster plume’s colour, deviating from the typical green-yellowish plasma [12] to a more pinkish plume, more typical of water vapour plasmas [11]. The combination of the high background pressures and the humidity in the line caused the thruster to flicker sometimes and become more unstable with a stronger magnetic field.

Another constraint within the system was the maximum mass flow rate achievable by the water electrolyser, capped at 1.6 mg/s of oxygen. Although this was not a constraint for the thruster *WET-HET*, it posed a challenge for the *AQUAHET* thruster due to its larger geometry, demanding higher mass flows for stable operation.

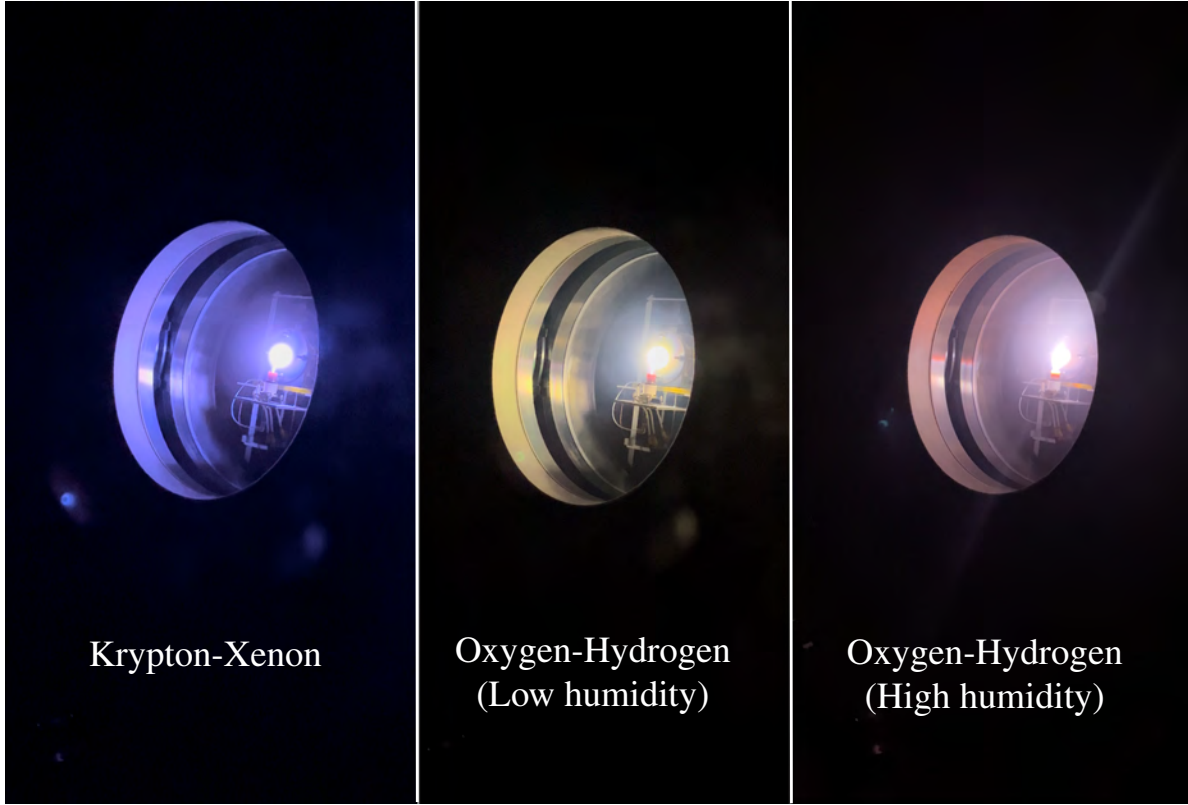


Fig. 9 Transition from xenon/krypton to water electrolysis (oxygen for the anode and hydrogen for the cathode) during the end-to-end experimental validation of the thruster *WET-HET* with the cathode *Hydrocat*.

This limitation hindered its stability with pure oxygen and hydrogen, although partial success was achieved by introducing a small fraction of xenon/krypton to sustain ignition in the discharge. In Section IV, various modifications to the facilities and water electrolyser fluidics are proposed to address these issues in subsequent tests.

Figure 10 shows an estimate of the total power requirements of a water electrolysis EP system. Reference values for the magnet, cathode keeper, cathode heater, and anode discharge power are taken from a firing test of the *WET-HET* and *Hydrocat* conducted at Imperial College London. For this firing, the anode current and voltage were 4.5 A and 434 V, respectively; the cathode keeper current and voltage were 2.5 A and 37 V, respectively; the cathode heater current and voltage were 6.5 A and 13 V, respectively; the magnet current and voltage were 1.5 A and 18.7 V respectively; and the anode and cathode were supplied with $\dot{m}_a = 1.0$ mg/s and $\dot{m}_c = 0.125$ mg/s of oxygen and hydrogen taken from compressed gas bottles. The total water electrolyzer power that would be needed to generate these anode and cathode mass flows (198 W, see Figure 5b) is used to calculate an estimate of the total power budget in the case of end-to-end, combined electrolyzer and thruster operation. It is estimated that 83% of the total system power would be consumed by the anode discharge, while the remaining portion would be distributed among the electromagnets, cathode (keeper and heater), and the water electrolyser.

Within the context of the water electrolyser, a significant 88% of the power is directed towards heating it to the operational temperature of 70°C. As mentioned in Section III.A and further elaborated here, this estimation is conservative. On one hand, the heating capacity of 175 W is utilised to raise the electrolyser's temperature to its operating temperature point. Once this temperature is achieved, the heating power required to maintain it is expected to be less. On the other hand, the design of the water electrolysis system is not oriented towards minimising power requirements, particularly in terms of heating. Therefore, this total heating power could potentially be reduced. Implementing a water electrolyser composed of thinner plates with a reduced heat capacity could substantially diminish the necessary heating [20]. However, even considering the most conservative scenario, the power prospects for water electrolysis EP systems are highly promising: adopting this technology, which inherently requires an onboard water electrolyser, does not incur significant penalties in terms of additional power requirements. As seen in Figure 10, it is anticipated a mere 8% of the overall power will be required by the water electrolyser.

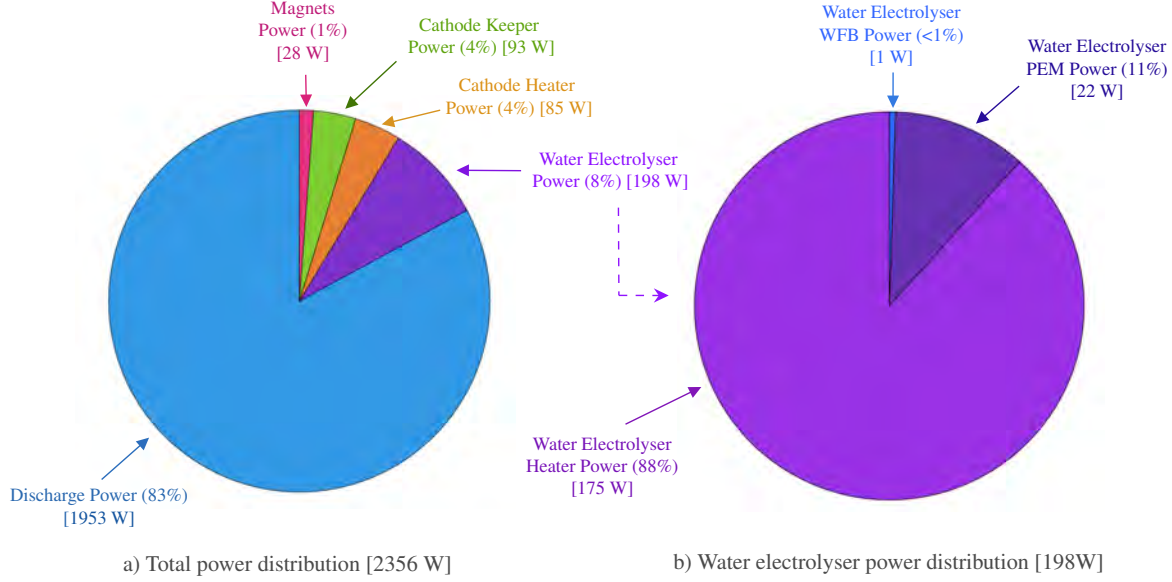


Fig. 10 Power distribution of the complete water electrolysis EP system (see Section III.C).

In terms of performance, these power requirements corresponded, for the thruster *WET-HET*, to a thrust of $T = 20.9 \pm 0.2$ mN, specific impulse of $I_{sp} = 2130 \pm 20$ s, thrust-to-power ratio of $TTPR = 10.7 \pm 0.5$ mN/kW, anode efficiency of $\eta_{tr} = 11.2 \pm 0.3\%$, and total efficiency of $\eta_{tot} = 10.1 \pm 0.3\%$ [16]. Notice that this data corresponds to the performance when using oxygen and hydrogen from pressurised bottles (not when oxygen and hydrogen are being produced by a water electrolyser, as firstly presented here). Although it is expected that the thruster's performance when using oxygen and hydrogen from pressurised cylinders versus produced by a water electrolyser should not change, this comparison is envisaged as one of the next step in the experimentation.

Current ongoing research is carried out to investigate other ways to maximise the performance of these systems, such as radiofrequency excitation [24, 25] and larger thruster mean diameters such as those featured in the *AQUAHET* thruster [18].

Nonetheless, it is expected that the HETs will not achieve the same performance levels as those powered by xenon, featuring $\sim 50\%$ anode efficiency. This disadvantage arises from the greater ionisation potential of oxygen (13.6 eV [26]) in contrast to xenon (12.1 eV [26]) and the different dissociation reactions of oxygen, (resulting in losses as they do not directly contribute to thrust generation). However, the disparity in weight between diatomic oxygen (32.0 g/mol [26]) and xenon (131.2 g/mol [26]) causes oxygen-fuelled HETs to exhibit a higher I_{sp} than those fuelled by xenon, albeit at the cost of lower thrust at a given power. This characteristic proves beneficial for deep-space missions necessitating higher I_{sp} values. All in all, water propulsion emerges as a robust candidate for short to medium-term space missions. This is mainly due to: 1) the synergies of water with other spacecraft subsystems, 2) its ubiquity in the solar system, 3) ISRU potential, 4) low cost and 5) the possible integration of a chemical propulsion (CP) system for high-thrust, low-specific-impulse manoeuvres [27, 28] alongside an EP system for low-thrust, high-specific-impulse manoeuvres—both powered by water.

D. Technology timeline

Figure 11 illustrates the timeline tracing the development of water propulsion technologies for HETs at IPPL, outlining the significant milestones pivotal in enabling this comprehensive technology validation.

The initial milestone traces its roots back to the end of 2018 when the conceptual framework of utilising the outputs from water electrolysis (oxygen for the thruster's anode and hydrogen for the cathode) was initially proposed [10].

At that juncture, minimal research had been done on oxygen-fuelled HETs [29], with very preliminary results on performance. Hydrogen-fed thermionic hollow cathodes, on the other hand, were thought to be more robust against emitter poisoning [30, 31], although their practical feasibility for space applications was yet to be further explored [32].

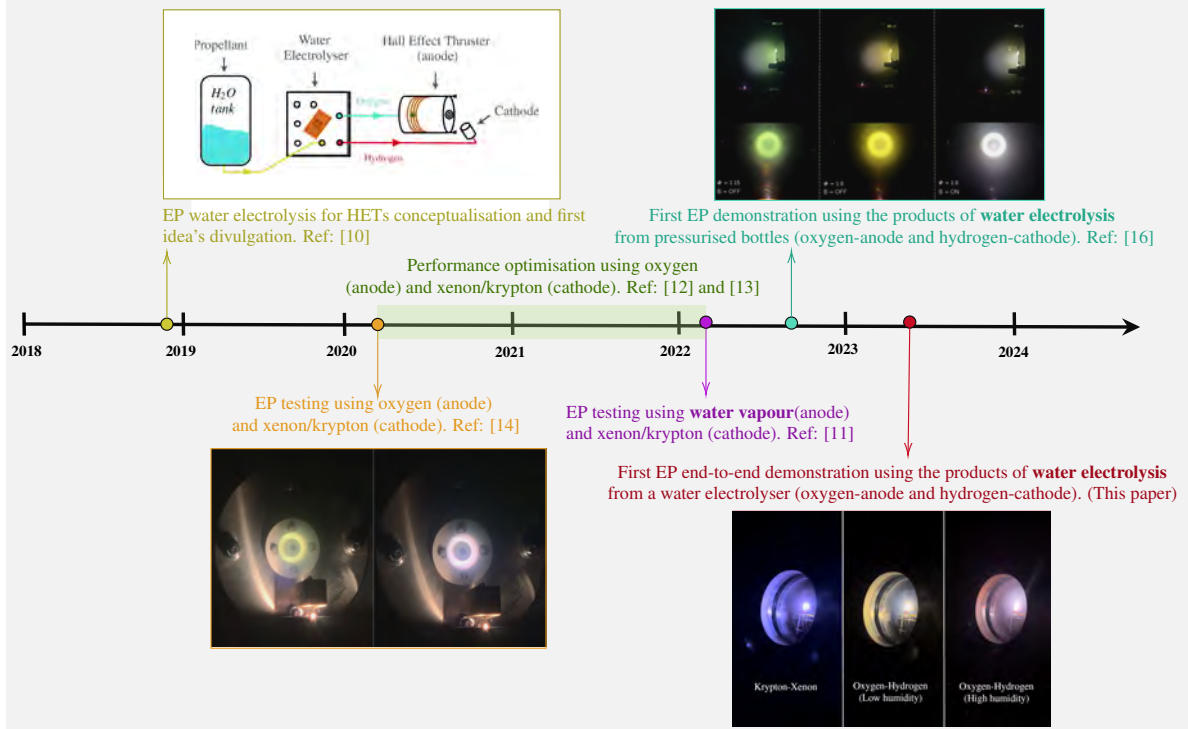


Fig. 11 Timeline of the water-fuelled electric propulsion Hall Effect Thrusters technology (either using the products of water electrolysis, oxygen (anode) and hydrogen (cathode) or using a direct water vapour feed).

It became evident that a foundational exploration of the underlying physics governing oxygen-fuelled thrusters and hydrogen-fuelled cathodes was imperative. This preliminary investigation aimed to ascertain the feasibility of this technology and define the specific conditions under which it could emerge as a viable option for future space missions. Specifically, the focus was on understanding the impact of oxygen on the discharge and performance of the thruster, as well as comprehending the oxidation effects on the surfaces exposed to the plasma.

To simplify the complexity of these experiments centred on the thruster (anode), xenon and krypton were employed to fuel the cathode. This approach facilitated the exploration of the anode discharge physics. These initial EP tests were conducted in early 2020 [14], marking the outset of exploring and refining the oxygen-fuelled thruster over the subsequent two years [12, 13]. Particularly, the inquiry delved into determining the most suitable channel length and anode and discharge channel wall material to ascertain the optimal thruster geometry and material choice, seeking compatibility and superior performance. Readers are redirected to this specific work for more details [12, 13].

Subsequently, an alternative option to water electrolysis emerged: a direct utilisation of water vapour (see Section I). By utilising water vapour instead of the products of water electrolysis, the need for an on-board water electrolyser is eliminated; thereby reducing cost, mass, and system complexity. A comparative assessment between water vapour and water electrolysis technologies under equal conditions using either water vapour or oxygen was conducted [11]. The findings revealed that under identical conditions, oxygen-fuelled HETs were approximately 20% more efficient than their water vapour-fuelled counterparts. Not only due to the better performance but because of a potential higher cathode compatibility (hydrogen in the case of water electrolysis versus water vapour or other propellant already onboard the spacecraft for a direct water vapour feed), the research into water electrolysis propulsion for HETs was intensified.

Upon concluding the initial investigation into the oxygen-fuelled thruster, the subsequent research phase involved the experimental demonstration of concurrent operation between an oxygen-fuelled thruster and a hydrogen-fuelled cathode. For this next experiment, both propellants were directly supplied via pressurised bottles. This milestone was achieved at IPPL in late 2022 [16]. This phase scrutinised the impact of Φ on the discharge process and assessed how the presence of hydrogen-oxygen plasmas influenced the integrity of the hardware.

The final milestone has been presented in this paper, encapsulating the successful testing of both the thruster (anode) and cathode using the products generated by a CVF water electrolyser (oxygen and hydrogen) supplied with liquid water. This campaign substantiated the feasibility of the technology, representing the worlds' first end-to-end demonstration of

water electrolysis fuelled HETs.

Lastly, notice that this timeline describes the experimental component of a long scale water electrolysis research program. Not covered here is the past and on-going efforts in numerically simulating these devices to understand the underlying physics and predict optimal performance configurations [15, 24, 25].

The future prospects for this technology are outlined within the next section.

IV. Conclusions and Future Work

In this work, the first end-to-end experimental demonstration of a water electrolysis HET working in combination with a water electrolyser was conducted. Liquid water was electrolysed to supply oxygen to the anode and hydrogen to the cathode at stoichiometric ratios.

To accomplish this, modifications were necessary at the ESA facilities to enhance safety when dealing with a stoichiometric mix of oxygen and hydrogen. Every pump used had an associated nitrogen purging system to dilute the gases entering the pump and avoid any potential explosive mixture. The water electrolyser fluidics were specifically designed to facilitate the feed of these gases into the system.

During the technology's validation, the water electrolyser operated under varied power conditions, allowing for diverse mass flows to the thruster (anode) and cathode, achieving up to 1.6 mg/s of oxygen and 0.2 mg/s of hydrogen under steady-state conditions. The predominant power consumption of the water electrolyser was directed towards heating, essential to maintain a temperature of 70 °C for optimal mass flow output. Despite the design of the water electrolyser not being optimised to minimise the power consumption, it is anticipated that the total power needed for the water electrolyser to run may correspond to just 8% of the total system power. In these conditions, the most substantial portion (83%) of the total system power would correspond to the anode discharge power.

As part of this discharge power also heats up the thruster, it could be investigated whether or not this heat can also be used to warm up the electrolyser up to the desired temperature; which will further ease the total power requirements. Overall, this bodes well for the technology, as the power overheads for incorporating a water electrolyser onboard spacecraft stand to constitute only a fraction of the overall power requirement. This consideration, together with other distinctive attributes of water, such as its potential for integrating both a CP and EP system, prospects for ISRU, synergies with astronaut life support systems, thermal cooling capabilities, cost-effectiveness, and environmental friendliness, position water as a highly promising candidate to fuel HETs for medium to long-duration space missions.

The next steps are directed towards the performance comparison between in-situ oxygen and hydrogen production versus the use of these gases from pressurised bottles. Specifically, to optimize thruster stability, desiccant beds should be utilized in the feed lines. This integration will mitigate the humidity originating from the gases produced by the water electrolyser. Moreover, having validated the safety of the ignition procedures within this test, a more sophisticated pumping system, incorporating the three pumping stages for the hatch and main chamber, can be implemented. This advancement will notably diminish the background pressure, enabling the HETs to operate within superior vacuum conditions.

Life-time tests of the technology using the lessons learnt from these experiments are also envisaged. From the thruster's standpoint, a comprehensive exploration of diverse coating layers is recommended to curtail the oxidation of stainless steel surfaces (in particular, the anode plate). This could largely improve the integrity of the HETs during long time firings. In this context, chromium and rhodium emerge as potential viable options owing to their low oxidation rates at elevated temperatures [33, 34].

Once the life-time tests conclude, an In-Orbit Demonstration (IOD) of this technology is strongly advised to promptly evaluate its performance in authentic space conditions. For that, the entire propulsion system (an engineering model and then a flight model with environmental qualification) should be prepared; including a compact propellant management assembly, power processing unit and control unit.

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