Joint Development of a Water Electrolysis Propelled Hall Effect Thruster and LaB_6 Hollow Cathode

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URA Thrusters Ltd., the Imperial Plasma Propulsion Lab, and Aliena Pte. Ltd. present a summary of the results of a collaboration for the development of a 1-2 kW level Hall effect thruster and accompanying LaB_6 hollow cathode designed to operate on the products of water electrolysis, i.e. oxygen to the anode and hydrogen to the cathode. A pseudo-2D version of the Imperial Plasma Propulsion Lab's fully kinetic particle-in-cell code, PlasmaSim, is used to size the discharge channel of the new thruster, termed AQUAHET. In parallel, a 0D plasma-thermal model is used by Aliena to size the emitter and orifice region of the hollow cathode, termed Hydrocat. Preliminary test campaigns are then carried out at both the Imperial Plasma Propulsion Lab and at Aliena's Jet Propulsion Test Facility. The Imperial preliminary campaign made use of a retrofitted version of an existing lab model thruster, the WET-HET, to provide benchmarking data to validate the AQUAHET discharge channel sizing. The Aliena preliminary campaign consisted of the thermal and discharge characterization of a prototype Hydrocat and guided improvements to the design of the engineering model cathode. After undergoing qualification and acceptance testing at the Aliena facility, the engineering model Hydrocat was shipped to Imperial for the project's final joint validation test campaign. The validation test campaign began with operation of the Hydrocat alongside the retrofitted WET-HET. This marked the first time a HET and hollow cathode had been successfully operated with oxygen to the anode and hydrogen to the cathode, a major milestone achievement for the project. Detailed experimental characterization of the AQUAHET and Hydrocat operating with oxygen and hydrogen followed. Best oxygen-hydrogen performance is obtained at 1168 ± 1 W for 1.7 mg/s of oxygen, 0.2 mg/s of hydrogen, 2.5 A of magnet current, with 20.0 ± 0.4 mN of thrust, 1216 ± 25 s of specific impulse, and 10.2 ± 0.4 % of anode efficiency measured at this set point. For reference, at 3200 ± 1 W for 1.7 mg/s of oxygen, 0.4 mg/s of krypton, and 5.5 A of magnet current, we measure 51.0 ± 0.5 mN of thrust, 3118 ± 32 s of specific impulse, and 24.4 ± 0.5 % of anode efficiency.

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I. Introduction and Background

As the most flown plasma thruster technology in both LEO and GEO, Hall effect thrusters (HETs) have played a key role in the recent market expansion of electric propulsion (EP).[1,2] Xenon was long considered the go-to propellant for these thrusters, with xenon-based HETs having accrued significant flight heritage since the first operation of two SPT-60s aboard the Meteor-18 satellite in 1971.[1,2] One of xenon's major advantages for electric propulsion is its ease of ionization, a consequence of a large ionization cross section coupled with a relatively low first ionization energy. As the heaviest of the non-radioactive noble gases, xenon allows for higher thrust-to-power ratios compared to other inert gases.[3] Xenon also offers relative ease of storage as it can be stored as a supercritical fluid.[3] One of the primary drawbacks of xenon is its prohibitive cost. Furthermore, as the global supply of xenon is limited, its price has been shown to be quite susceptible to fluctuations in demand from key stakeholders.[4,5] The projected continued expansion of the EP market is expected to further exacerbate these pricing and availability issues, highlighting a real market need for viable alternatives to xenon.

Thus far, research into alternative propellants for EP has centered on inert gases like krypton,[6,7] on the halogen iodine,[4,8] and has also extended to a variety of metals like magnesium,[9] zinc,[10] and bismuth.[11] In recent years, water has also emerged as a promising potential alternate for HETs. Water is ubiquitous on earth, is undoubtedly lower cost than xenon, and comes with a variety of potential system level benefits. Water can be stored as a liquid at densities higher than krypton.[12] Additionally, as it can be stored at low pressures propellant tank mass can be saved compared to xenon. Water is also easy to transport and is non-hazardous. This removes the need for specialized propellant loading equipment and personnel, reducing launch site activity complexity and associated costs.

Motivated by these potential benefits, URA Thrusters and the Imperial Plasma Propulsion Laboratory (IPPL) have begun research into the use of water as a propellant for HETs. This URA-IPPL collaboration sits within the framework of a larger joint R&D effort for the development of a novel hybrid chemical-electric propulsion architecture that uses water as a unified propellant, HYDRA (see Figure 1). When higher thrust maneuvers are required, the HYDRA system relies on a Micro Electro-Mechanical Systems (MEMS) based bi-propellant chemical thruster, the Iridium Catalyzed Electrolysis (ICE) thruster.[13,14,15] When high mass utilization efficiency is important, the HYDRA system can rely on a HET fueled in one of two ways. In the first configuration, the oxygen and hydrogen produced through water electrolysis are fed to the anode and cathode respectively. In the second configuration, the anode is fueled directly with water vapor and the cathode can be fed with an inert gas.

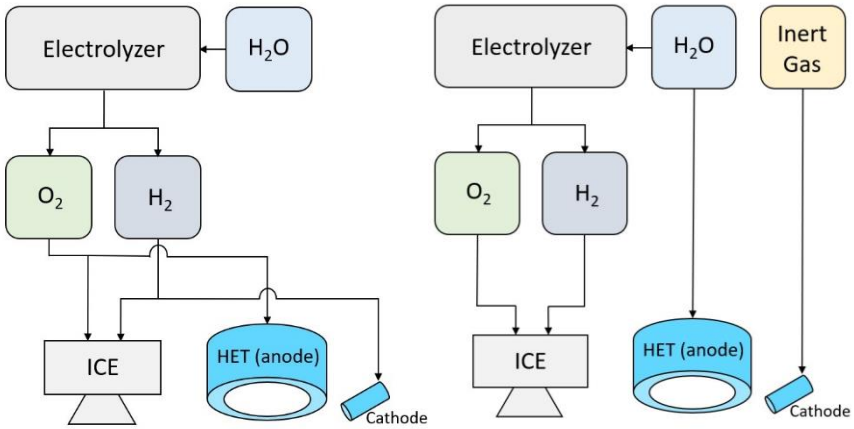

Figure 1. Schematic of the HYDRA architecture with a water electrolysis-based HET (left) and a water vapor based HET (right).

The following paper will describe the outcomes of a recent collaboration between URA Thrusters Ltd., the Imperial Plasma Propulsion Laboratory, and new partner in the development Aliena Pte. Ltd. for the design, build, and test of an engineering model 1-2 kW level water-fueled HET and accompanying LaB_6 hollow cathode, termed AQUAHET and Hydrocat respectively. While efforts within the project were undertaken to design a system compatible with operation using both the products of water electrolysis (i.e. oxygen to the anode and hydrogen to the cathode) and

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water vapor (i.e. water vapor to the anode and a compressed gas to the cathode), we will focus here primarily on the water electrolysis related results.

This project, undertaken thanks to the generous support of a joint Innovate UK and Enterprise Singapore grant administered as part of the Eureka Globalstars program, had as its primary objective to obtain the world's first performance measurements of a HET operating on the products of water electrolysis, oxygen and hydrogen. In order to describe how this was achieved, the project timeline will be split into three phases, as can be seen in Figure 2, with key outcomes for each phase summarized in the following paper sections. Section II will describe key outcomes for Phase 1 (State-of-the-art (SOTA)/System Requirements Review (SRR) to Preliminary Design Review (PDR)), section III those for Phase 2 (PDR to Critical Design Review(CDR)/Manufacturing Readiness Review(MRR)), and section IV those achieved in Phase 3 (CDR/MRR to Final Review (FR)).

Figure 2. Joint Innovate UK and Enterprise Singapore project timeline.

II. Phase 1: State-of-the-art (SOTA)/System Requirements Review(SRR) to Preliminary Design Review (PDR)

A. AQUAHET Discharge Channel Sizing

The concept of a Hall thruster designed to operate on the products of water electrolysis was first proposed by Schwertheim and Knoll at the 16th Reinventing Space (RiSpace) Conference in 2018.[16] Early design work for the oxygen-based thruster (anode) within the IPPL began with initial sizing of the discharge channel length, width, and mean diameter. This was carried out using a simplified quasi-0D version of the IPPL's fully kinetic particle-in-cell (PIC) code, PlasmaSim. Optimizing for 1-2 kW level oxygen operation, a thruster with channel lengths of 35-60 mm, a channel width of 5 mm, and a channel mean diameter of 20 mm was proposed.[17] The laboratory model thruster subsequently built, referred to internally as the Water ElecTrolysis Hall Effect Thruster or WET-HET, can be seen pictured in Figure 3. It then underwent subsequent extensive performance characterization at the IPPL, as detailed in references herein.[18,19]

Figure 3. Laboratory model WET-HET thruster (taken from Ref. 19).

As the simplified quasi-0D version of PlasmaSim used for the design of the WET-HET had shown a mismatch with early experimental oxygen performance data collected, IPPL researchers started by working to integrate one of

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the key energy loss mechanisms in oxygen plasmas, non-ionizing dissociation, into an improved pseudo-2D version of the code.[20,21] It was found that this addition significantly improved PlasmaSim's predictive capabilities for oxygen, with simulation results now matching more closely with experimental data.[20,21] The successful leveraging of oxygen data collected with the lab model WET-HET highlighted how important having access to experimental benchmarking data can be in helping guide the development of novel simulation tools.

Preliminary design of the second generation engineering model AQUAHET thruster within the scope of the Innovate UK/Enterprise Singapore project began, as it had with the lab model WET-HET, with discharge channel sizing using the improved pseudo-2D version of PlasmaSim. Applied in this case to a water plasma, the code evaluated performance for discharge channels with lengths between 7 and 21 mm, widths between 3 and 5 mm, and mean diameters between 15 and 25 mm. An example of the sizing simulation data used is shown in Figure 4, with further data available in Ref. 21. Note that though the simulations for the discharge channel sizing were carried out for water plasma, it was anticipated that they would still yield a channel geometric configuration suitable for oxygen operation. Note also that the presence of multiple high anode efficiency points clearly pointed to further sources of unaccounted losses in the water-based pseudo-2D implementation of PlasmaSim used. Given the relative uncertainty associated with the PIC modeling predictions it was decided that a thruster with a modular channel geometry would be built. Channel lengths of 7, 10 and 13 mm, channel widths of 3, 4, and 5 mm, and a mean diameter of 20 mm were selected at this design stage. A preliminary CAD model was then prepared around this channel sizing with thruster overall design characteristics matching that of conventional HETs (see Figure 4).

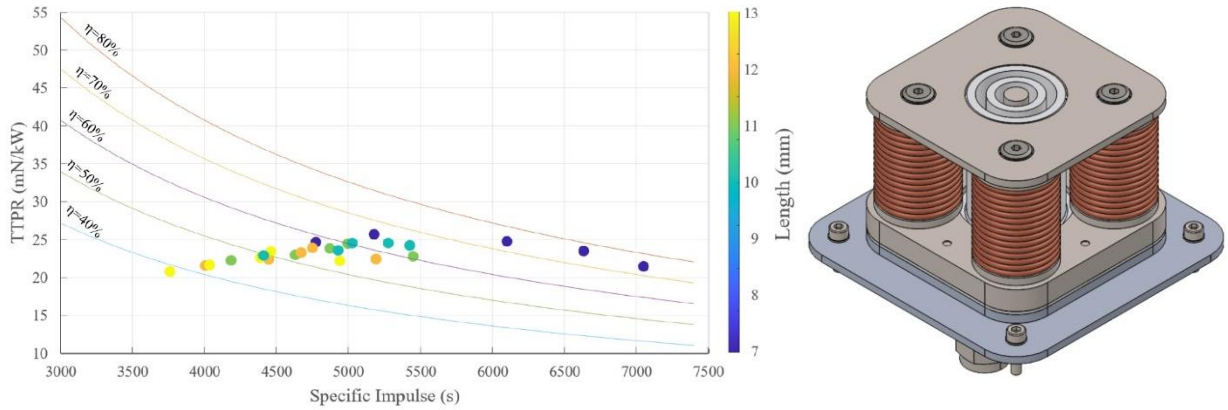

Figure 4. Left: Simulated thrust-to-power ratio as a function of specific impulse for a water fueled HET with channel lengths 13-21 mm, widths 3-5 mm, mean diameter 15-25 mm (taken from Ref. 21). Right: CAD model of the AQUAHET at the PDR stage.

B. Hydrocat Emitter Sizing

In parallel to thruster (anode) discharge channel sizing activities at URA/IPPL, Aliena worked to further the preliminary design of the Hydrocat cathode. More specifically, Aliena made use of their existing in-house 0D plasma-thermal model to scale the emitter and orifice region of the cathode.[22, 23]

The cathode overall preliminary mechanical design closely followed the design of the company's existing low-current cathode. Meaning that it featured an orificed geometry and an emitter made of LaB_6. The main design considerations that applied to the Innovate UK/Enterprise Singapore project specifically were that the emitted current should vary between 2 and 10 A, and that the cathode should be able to demonstrate self-sustained operation when operating with hydrogen and heavier gasses such as nitrogen.

The Aliena 0D plasma-thermal model consisted of a plasma solver and a thermal solver coupled together in order to allow for a self-consistent estimation of the cathode power budget in self-sustained operation. The plasma solver was based on models developed by Domonkos and Gurciullo et al. and considered both the ion and electron

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contributions to the current and power balance equations.[24,25] The thermal solver was implemented in FEMM, receiving as inputs the geometry of the cathode and the power deposited by the plasma on the various internal regions and outputting insert temperature for the plasma solver's next iteration. Figure 5 shows a schematic of the two main computational regions considered in the code. For a more complete description of the plasma-thermal model, readers are directed to the studies presented by Potrivitu et al. which can be found in Refs. 22& 23.

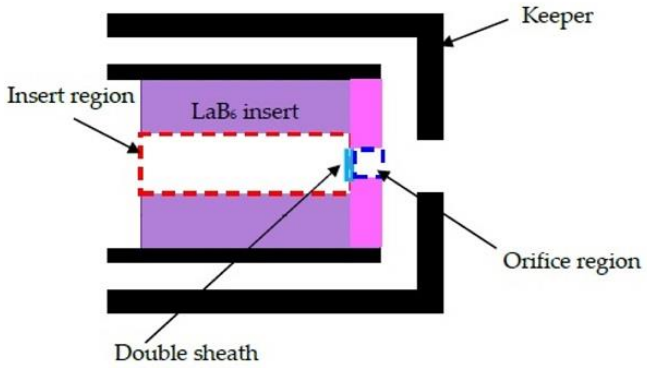

Figure 5. Orificed cathode schematic showing the two main computational regions considered (based on Ref. 30).

C. Summary of Outcomes

The main outcomes at the PDR stage of the project were AQUAHET discharge channel and Hydrocat emitter and orifice sizing. The AQUAHET discharge channel was sized for 1-2 kW level water/oxygen operation, with channel lengths of 7-10-13 mm, channel widths of 3-4-5 mm, and a mean diameter of 20 mm selected. The Hydrocat was sized for operation with hydrogen and heavier gasses like nitrogen at emitted currents between 2 and 10 A. In the case of the AQUAHET, preliminary CAD was also prepared.

III. Phase 2: Preliminary Design Review (PDR) to Critical Design Review (CDR)/Manufacturing Readiness Review (MRR)

A. AQUAHET Engineering Model Design

While the pseudo-2D version of PlasmaSim used for the AQUAHET discharge channel sizing carried out during Phase 1 of the project had shown good predictive capabilities for oxygen-based simulations, water-based simulations had yet to be cross checked against experimental data. Experimental verification of the water simulations was considered especially critical in this case as numerical results had clearly pointed to sources of unaccounted losses in the code.[21] It was therefore decided that a preliminary experimental campaign would be carried out to provide researchers with benchmarking data to de-risk the AQUAHET critical design phase. As such, parts were manufactured to retrofit available WET-HET thruster hardware with a discharge channel of 6 mm and 13 mm length. Note that while the WET-HET lab model had previously been tested with oxygen at a channel width and mean diameter of 5 and 20 mm respectively, only channel lengths between 35 and 60 mm had been tested.

The preliminary simulation verification test campaign was carried out in the IPPL's Boltzmann vacuum chamber using a WET-HET lab model thruster retrofitted with a boron nitride discharge channel of length 6 and 13 mm, width 5 mm, and mean diameter 20 mm. For the purposes of these tests, a plasma bridge neutralizer operating with 5 to 15 sccm of krypton was used. Performance data was collected with the IPPL's hanging pendulum style thrust balance at 1.0 mg/s of oxygen and 0.7-1.0 mg/s of water vapor to the anode for discharge powers up to approximately 2240 W.

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A detailed description of the experimental setup and results can be found in two studies by Tejeda and Knoll.[26,27] Key takeaways for the oxygen testing were that the 13 mm length channel outperformed all other channel lengths tested thus far. Highest thrust was recorded at 2238 ± 1 W with 1 mg/s of oxygen flow to the anode and a magnet current of 1.5 A. At this power level, 27.0 ± 0.2 mN of thrust, 2874 ± 21 s of specific impulse, and 17.00 ± 0.25 % of anode efficiency were measured.[26] Key takeaways from the water vapor testing were that oxygen outperformed water. In this case, highest thrust was recorded at 1600 ± 1 W with 1.0 mg/s of water vapor flow to the anode and a magnet current of 1.5 A. At this set point, 20.0 ± 0.2 mN of thrust, 2039 ± 20 s of specific impulse, and 12.5 ± 0.3 % of anode efficiency were measured.[27]

As was described by Rosati Azevedo et al. and as had been expected from the sizing simulation results, the pseudo-2D version of PlasmaSim used was able to provide estimates of the water vapor performance, albeit with limitations.[21] This is evident in Figure 6 below, and was attributed to an inadequate capture of the collision physics. Indeed, in a water plasma more energy is lost to non-ionizing electron-neutral collisions compared to oxygen plasma, making the case for a revised approach to collision modeling. Research efforts have since been made to address this shortcoming and will be the subject of an upcoming publication.[28] Despite the lower than anticipated water performance results, the retrofitted WET-HET showed improved performance with oxygen flow to the anode for the new channel sizes, giving URA increased confidence in the sizing selected at the PDR stage. However, due to various restrictions imposed by thermal and magnetic field topology requirements, the channel sizing recorded at CDR changed to lengths of 7-10-13 mm, channel widths of 4-5 mm, and a mean diameter of 40 mm. The full CAD model of the resultant AQUAHET design can be seen in Figure 6.

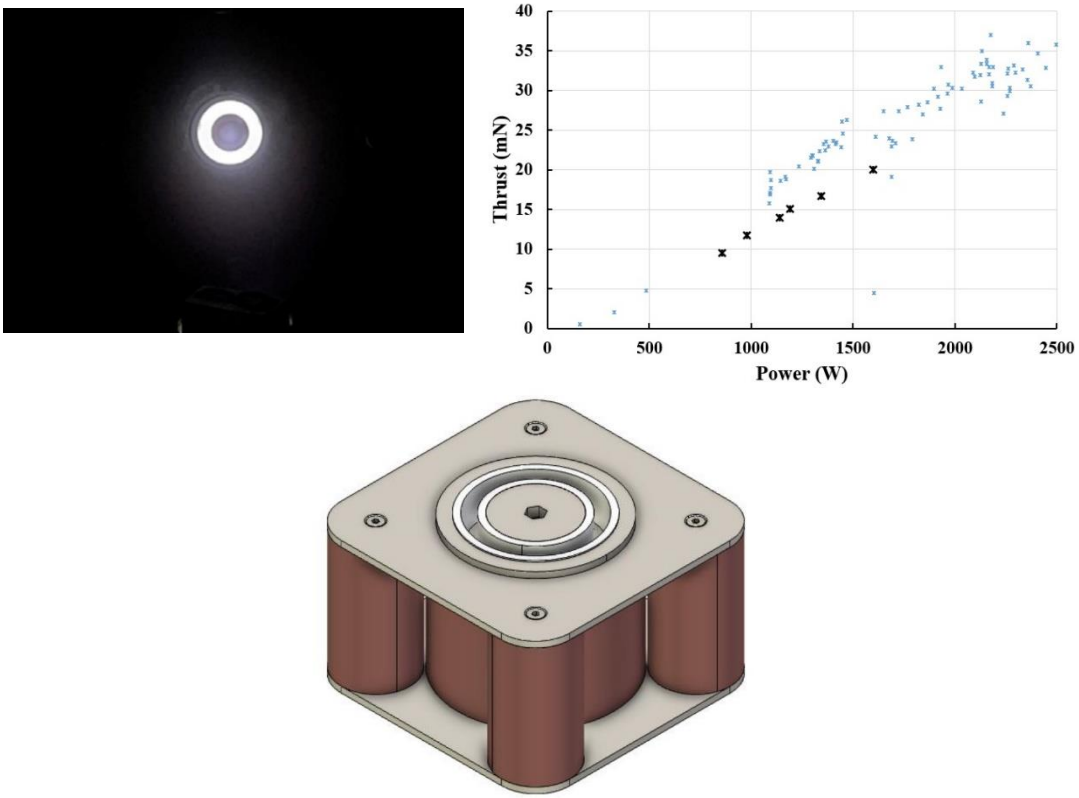

Figure 6. Top Left: Retrofitted WET-HET firing with oxygen (taken from Ref. 26). Top Right: Comparison between PlasmaSim predictions (blue) and experimental data (black) collected at the IPPL facilities using the WET-HET running on 1.0 mg/s of water, a magnet current of 1.5 A, and with a 13 mm long channel (taken from Ref. 21). Bottom: CAD of the AQUAHET at CDR stage.

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B. Hydrocat Engineering Model Design

Using the emitter sizing results from the 0D plasma-thermal model briefly described in Section II.B, and following similar mechanical design principles to those used for the company's low-current cathodes, Aliena built a prototype of the Hydrocat (see Figure 7).

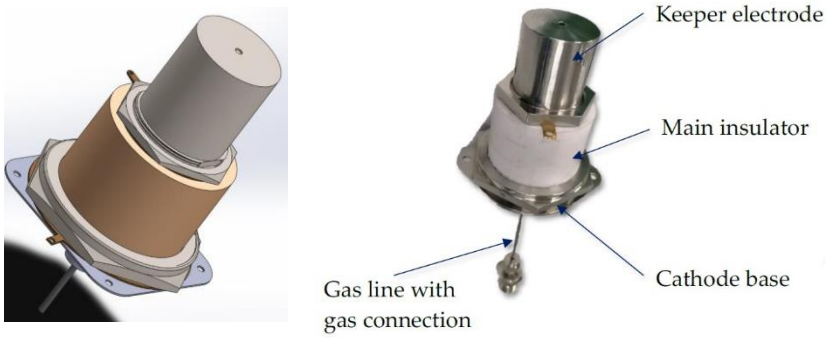

Figure 7. Left: CAD model of the prototype model Hydrocat. Right: Prototype model Hydrocat.

The Hydrocat prototype then underwent detailed thermal characterization, as well as diode and triode mode testing at Aliena's Jet Propulsion Test Facility. The thermal tests were carried out in the SC-001 vacuum chamber and were aimed at characterizing the heater circuit and overall thermal management of the cathode, with results compared to outputs from the FEMM simulations.

Ignition tests, as well as operational envelope and discharge stability characterization took place in the MC-003 vacuum chamber with xenon, krypton, argon and nitrogen. Discharge characteristics were monitored with a series of voltage and current probes. Discharge stability in terms of operational mode, i.e., spot or plume mode, was assessed using the mode transition criterion introduced by Sary et al. and based on the oscillation level of the anode current.[29] Ignition was achieved, an operational envelope successfully established, and spot mode observed for xenon, krypton and argon (see Figure 8). Additionally, for each of these three gases, the prototype cathode was able to operate in self-sustained mode (without heating and keeper power). Operation with nitrogen, though attempted, unfortunately did not yield successful ignition.

For a more complete accounting of the above prototype characterization testing, readers are once again re-directed to the study presented by Potrivitu et al.[30]

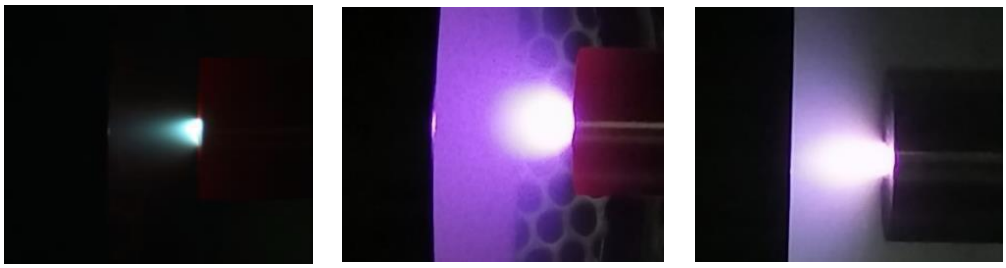

Figure 8. Prototype model Hydrocat operating in standalone mode with an external cylindrical anode at 4 A with 5.15 sccm xenon (left), 5.15 sccm krypton (center), and 12.1 sccm argon (right).

Lessons learnt from the experimental characterization of the prototype guided improvements to the heater circuit and ceramics, to the keeper material selection, and to elements of design such as the inter-electrode distance. These improvements were integrated into the design of a engineering model Hydrocat which was subsequently manufactured (see Figure 9).

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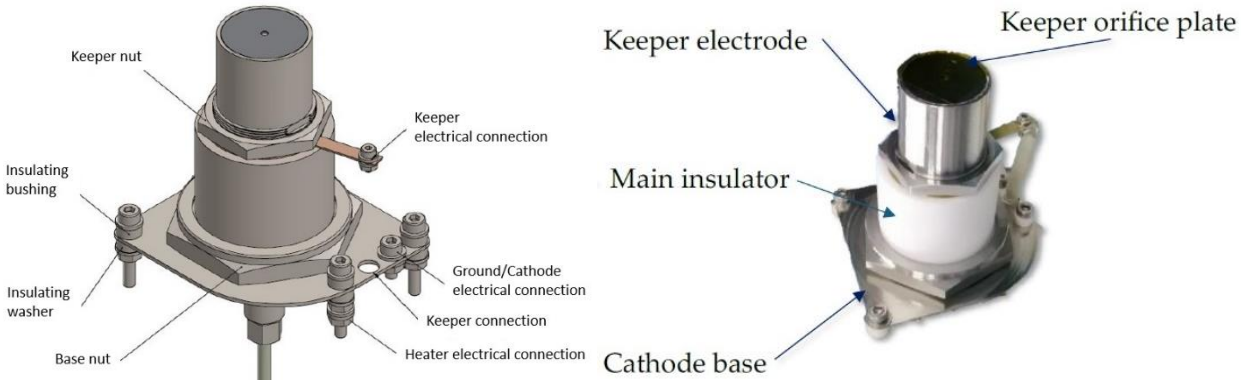

Figure 9. Left: CAD model of the engineering model Hydrocat. Right: Engineering model Hydrocat.

C. Summary of Outcomes

A preliminary test campaign carried out at the IPPL facilities with a WET-HET retrofitted to accommodate a discharge channel with a 13 mm length, a 5 mm width, and a 20 mm mean diameter was used to validate the PlasmaSim sizing runs described in Section II.A. For these tests, the thruster (anode) was fed with both oxygen and water vapor, and was operated alongside a plasma bridge neutralizer running on krypton. Due to thermal and magnetic topology related requirements, changes followed during the critical design phase, with channel lengths of 7-10-13 mm, channel widths of 4-5 mm, and a mean diameter of 40 mm ultimately selected for the engineering model AQUAHET. A prototype of the Hydrocat underwent thermal characterization as well as diode and triode mode testing with xenon, krypton, argon, and nitrogen at the Aliena facilities. Lessons learnt from the prototype testing enabled the design of the engineering model Hydrocat.

IV. Phase 3: Critical Design Review (CDR)/Manufacturing Readiness Review (MRR) to Final Review (FR)

A. Engineering Model Hydrocat Qualification and Acceptance Testing

Following successful completion of the cathode CDR and MRR, Phase 3 of the project began with the manufacture and assembly of three engineering model cathodes (see Figure 9). It was envisaged that one cathode would be used for a full qualification campaign, with the two remaining cathodes due for acceptance testing before delivery to the IPPL for the project's final joint AQUAHET-Hydrocat validation test campaign.

The engineering model qualification campaign followed the same plan as for the prototype cathode tests described in Section III.B. Work began with heater and thermal management characterization, and was followed by discharge tests with various gases (xenon, krypton, argon, and nitrogen). Once again, the campaign was carried out at Aliena's Jet Propulsion Test facility, with heater/thermal tests taking place in the SC-001 vacuum chamber, and discharge tests taking place in the MC-003 vacuum chamber.

Given that the heater circuit and ceramics for the engineering model Hydrocat had been updated following preliminary testing of the prototype cathode, it was necessary to characterize the thermal behavior of the new design. Heater and thermal management characterization testing provided valuable insights, with results confirming health of the new heating circuit and showing its ability to bring the emitter/orifice plate of the cathode to emission temperatures corresponding to at least 0.5 A, the typical keeper current during ignition.

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The subsequent discharge tests were carried out in triode configuration with the keeper electrode and an external circular anode. As had been observed during the prototype cathode preliminary testing, the engineering model cathode ignition was achieved and an operational envelope collected for xenon, krypton, and argon (see Figure 10). Spot mode was observed for xenon and krypton. Operation with nitrogen, though again attempted, did not yield successful ignition.

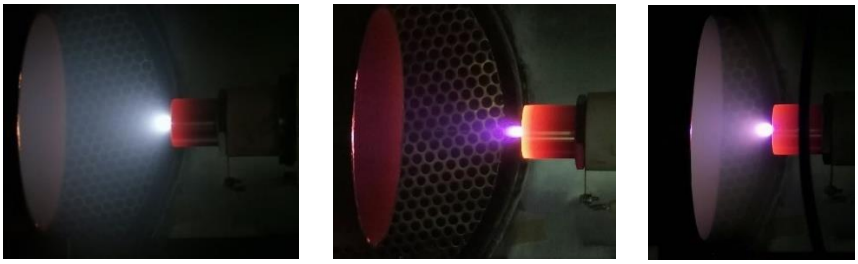

Figure 10. Engineering model Hydrocat operating with an external cylindrical anode with: Left – 4 A anode current, 0.85 A keeper current, 3.13 sccm xenon, Center – 2 A anode current, 0.85 A keeper current, 5.45 sccm krypton, Right – 4 A anode current, 1 A keeper current, 12.1 sccm argon.

Once the qualification test campaign had been concluded, the two remaining Hydrocat engineering model cathodes were subjected to acceptance testing ahead of their shipment to the IPPL facilities. Both cathode heaters passed acceptance testing in the SC-001 chamber having successfully demonstrated their ability to provide the necessary heating power. Cathode heating and ignition sequence tests with argon in the MC-003 chamber followed, with both cathodes reliably igniting. The cathodes then showed stable operation with argon both in triode mode over the range of anode current from 1.5 to 6 A with 1 A of keeper current, as well as in diode mode.

Having successfully passed acceptance tests, the two cathodes were shipped to the IPPL facilities in anticipation of the final validation test campaign for the project. Note that as in the previous cathode sections, readers are directed to the Potrivitu et al. study for a more detailed accounting of the above qualification and acceptance tests.[30]

B. Final Joint Validation Testing with Oxygen and Hydrogen

The final joint experimental validation campaign of the retrofitted lab model WET-HET (channel length 13 mm, width 5 mm, and mean diameter 20 mm) and the engineering model AQUAHET (channel length 7-10-13 mm, widths 4-5 mm, and mean diameter 40 mm) operated with the Hydrocat received from Aliena took place at the IPPL using oxygen and hydrogen from compressed gas bottles. Thrust measurements were collected for this campaign in the Boltzmann vacuum chamber using the group's hanging pendulum style thrust balance. Note that the use of oxygen and hydrogen from compressed gas bottles required the implementation of stringent health and safety procedures. This included the use of a bespoke hydrogen fluidics board kept in vacuum and fitted with hydrogen plena tanks that were filled and emptied (in between nitrogen purge cycles of the chamber) on a daily basis. A detailed description of the full setup used, including accounting of the main H&S considerations, can be found in a series of studies by Tejeda et al.[31,32] What will follow in this section is a brief summary of the key results obtained with the WET-HET+Hydrocat and AQUAHET+Hydocat operated with oxygen to the anode and hydrogen to the cathode.

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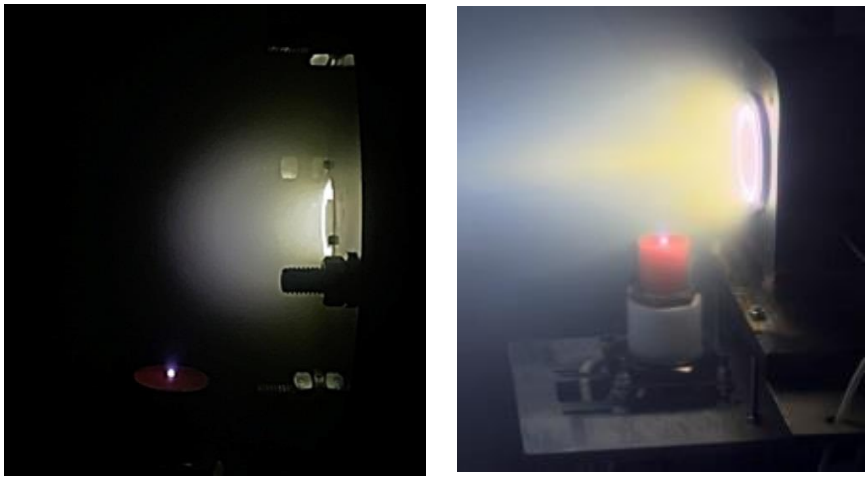

Figure 11. Retrofitted WET-HET+Hydrocat and AQUAHET+Hydrocat firing with oxygen to the anode and hydrogen to the cathode (taken from Refs. 31&32).

Testing started with the retrofitted WET-HET (channel length 13 mm, width 5 mm, and mean diameter 20 mm) firing alongside the Hydrocat and marked the first successful operation of a HET with oxygen to the anode and hydrogen to the cathode (see Ref. 31). This was a major milestone achievement for the project and for the HYDRA architecture development as a whole. Figure 12 shows thrust, specific impulse, and anode thrust efficiency for the retrofitted WET-HET and Hydrocat operated with 1.0 mg/s oxygen to the anode, 0.04 to 0.17 mg/s hydrogen to the cathode (corresponding to hydrogen-to-oxygen (Φ) ratios from 1:6 to 1:25), and 1.5 A of magnet current. These datasets were collected at discharge power levels between 200 and 2000 W. As can be seen from the plot, thrust performance is not impacted by the change in cathode mass flow, a phenomenon discussed in more detail in Ref. 31 herein. Best performance is obtained at 1953 ± 1 W for Φ = 1:25. At this point, 20.9 ± 0.2 mN of thrust, 2130 ± 20 s of specific impulse, and 11.2 ± 0.3 % of anode efficiency were measured.

The final validation test campaign of the project also saw the AQUAHET (channel length 7-10-13 mm, width 4-5 mm, and mean diameter 40 mm) and Hydrocat successfully operated with oxygen to the anode and hydrogen to the cathode.[32] The AQUAHET here was tested at channel lengths of 13 mm and widths of 4 and 5 mm. Figure 12 shows thrust, specific impulse, and anode thrust efficiency for the 4 mm width AQUAHET and the Hydrocat operated with 1.7 mg/s oxygen to the anode, 0.05 to 0.2 mg/s hydrogen to the cathode (corresponding to hydrogen-to-oxygen Φ ratios from 1:8 to 1:35), 2.5 A of magnet current, and at discharge power levels up to roughly 1200 W. Once again, no discernable difference in thrust is measured as a function of cathode mass flow.[32] Note that compared to the WET-HET, the AQUAHET achieves higher thrust but lower specific impulse at similar power levels. This can be in part attributed the difference in anode surface area resulting from the difference in channel mean diameter between the two thrusters. This naturally impacts the thruster mass flow operational envelope, and so the anode mass flow the thrusters are typically operated at, here 1.0 mg/s for the WET-HET versus 1.7 mg/s for the AQUAHET. In this case, best performance of the AQUAHET is obtained at 1168 ± 1 W for Φ = 1:8 where 20.0 ± 0.4 mN of thrust, 1216 ± 25 s of specific impulse, and 10.2 ± 0.4 % of anode efficiency were measured.

In the interest of simplifying the health and safety procedures required to operate the thruster, a number of datasets within this campaign were collected with krypton flow to the cathode. Though a performance boost is observed when compared to operation with hydrogen flow to the cathode, it was considered that the trends measured would still remain valid.[32] Most optimum performance is obtained for the 5 mm width AQUAHET and Hydrocat operated with 1.7 mg/s oxygen to the anode, 0.4 mg/s krypton to the cathode, 5.5 A of magnet current, and 3200 ± 1 W of discharge power, and is provided here as a reference. At this set point, 51.0 ± 0.5 mN of thrust, 3118 ± 32 s of specific impulse, and 24.4 ± 0.5 % of anode efficiency were measured.

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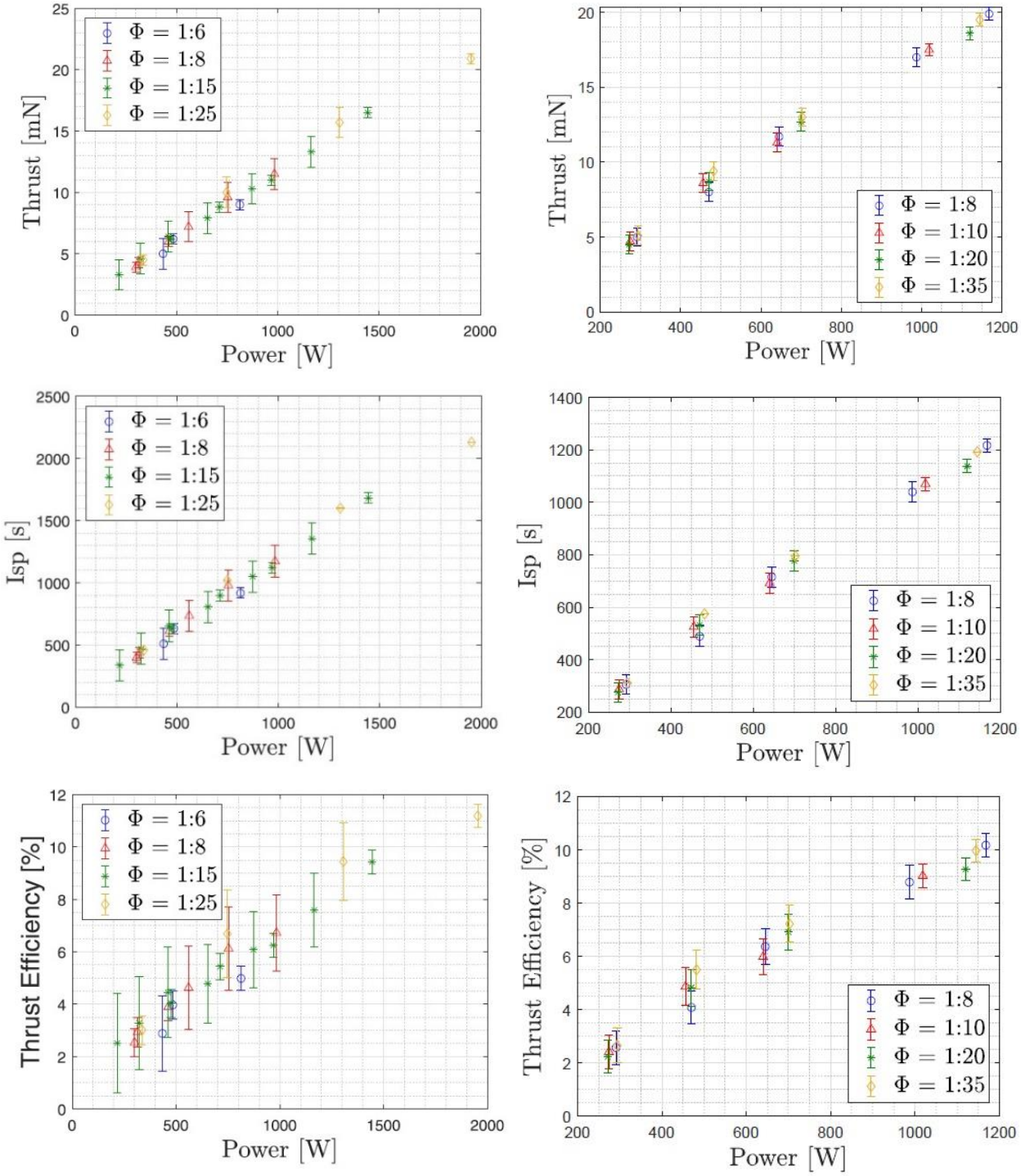

Figure 12. Left: Experimental measurements of the retrofitted WET-HET (13 mm channel length) and engineering model Hydrocat operating with 1.0 mg/s oxygen to the anode, 0.04 to 0.17 mg/s hydrogen to the cathode, and 1.5 A of magnet current (taken from Ref. 31). Right: Experimental measurements of the AQUAHET (channel: 13 mm length, 4 mm width) and engineering model Hydrocat operating with 1.7 mg/s oxygen to the anode, 0.05 to 0.2 mg/s hydrogen to the cathode and 2.5 A of magnet current (taken from Ref. 32).

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V. Conclusion

Testing of the IPPL's existing laboratory model thruster, the WET-HET, retrofitted to accommodate a channel of length 13 mm, width 5 mm, and mean diameter 20 mm yielded improvements for oxygen operation compared to earlier versions of the lab model, though water vapor performance was less promising than had been expected from PlasmaSim predictions. This early test campaign provided valuable early benchmarking data for the purposes of guiding improvements to PlasmaSim, and significantly de-risked the thruster (anode) detailed design phase, facilitating the design and manufacture of the modular engineering model AQUAHET thruster fitted with channel lengths of 7-10-13 mm, channel widths of 4-5 mm, and a mean diameter of 40 mm. Thermal and discharge characterization of a prototype Hydrocat was also instrumental in guiding design improvements for the subsequent engineering model Hydrocat.

The final joint performance characterization campaign for this project began with validation of Hydrocat operation alongside the retrofitted WET-HET. This marked the first time a HET and hollow cathode had been successfully operated with oxygen to the anode and hydrogen to the cathode, a milestone achievement for the project. Best performance obtained within this campaign with oxygen to the AQUAHET (4 mm width) and hydrogen to the Hydrocat was obtained at 1.7 mg/s of oxygen, a Φ=1:8 ratio, and 2.5 A of magnet current at a discharge power level of 1168 ± 1 W. At this set point, 20.0 ± 0.4 mN of thrust, 1216 ± 25 s of specific impulse, and 10.2 ± 0.4 % of anode efficiency were measured. Best performance with oxygen to the AQUAHET (5 mm width) and krypton to the Hydrocat was obtained at 1.7 mg/s of oxygen, 0.4 mg/s of krypton, and 5.5 A of magnet current at a discharge power level of 3200 ± 1 W. At this set point, 51.0 ± 0.5 mN of thrust, 3118 ± 32 s of specific impulse, and 24.4 ± 0.5 % of anode efficiency were measured.

The achievement of the world's first operation of a HET using oxygen and hydrogen constitutes a major success for the project and an important step in the development of the propulsion system towards a commercial product. The recent operation of the WET-HET and Hydrocat with the oxygen and hydrogen produced by an electrolyzer operating in air, as opposed to being provided by compressed gas cylinders as had been done for this project, also constitutes a positive step forward.[33] As encouraging as these advancements are, much remains to be done. In future work, the AQUAHET and Hydrocat will be operated with the by-products of an electrolyzer operating in-situ, meaning an electrolyzer operating under vacuum conditions. Research to identify suitable materials or coatings to mitigate for the oxidation of metallic surfaces in the presence of oxygen plasma will also be key. Finally, work will be carried out to mitigate for lifetime limiting issues observed when operating the cathode with hydrogen.

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