# The Water Electrolysis Hall Effect Thruster (WET-HET): Paving the Way to Dual Mode Chemical-Electric Water Propulsion.

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**We propose that a Hall Effect Thruster (HET) could be modified to operate on the hydrogen and oxygen produced by the in situ electrolysis of water. Such a system would benefit from the high storage density, low cost and prevalence of water, while also increasing specific impulse. The poisoning of traditional Lanthanum Hexaboride cathodes can be mitigated by operating the thruster on oxygen but the neutraliser on hydrogen. The proposed hydrogen/oxygen electric propulsion system can be combined with a hydrogen/oxygen chemical propulsion system, granting a spacecraft dual mode propulsion capabilities. Such a system architecture saves mass by utilising a single propellant storage and management system, yet can perform both high thrust chemical burns and high impulse electric burns, unlocking novel mission trajectories not possible with a single propulsion system. Even further mass saving can be achieved by replacing traditional batteries with a fuel cell system, combining power storage and propulsion into a single system architecture.**

**The Water Electrolysis Hall Effect Thruster (WET-HET) is presented. The channel dimensions have been optimised for oxygen operation using PlasmaSim, a zero dimensional particle-in-cell model developed in-house. We validate the effectiveness of PlasmaSim to optimise a thruster geometry by conducting a sensitivity analysis on a conventional SPT100 thruster operating on xenon. Good agreement is found. The WET-HET has been optimised to operate on 50 sccm of oxygen, at 1-2 kW with an outer channel diameter of 25 mm, channel width of 5 mm and variable channel depth between 35 mm and 60 mm. Magnetic and thermal designs of the WET-HET are presented. Due to the lower ionisation cross section of oxygen in comparison with xenon, a longer magnetisation region is applied. The WET-HET design allows for the magnetisation region of the thruster to be increased or decreased easily during testing.**

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# I. Introduction

With very few exceptions, all current flown plasma propulsion systems rely on operating both the thruster and the neutraliser on xenon. This propellant offers a unique combination of a low ionisation energy, large ionisation cross section, low chemical reactivity, and high storage density. Growing concerns of the high and volatile price of xenon are driving the need for alternative propellants.[1,2] Other nobel gases such as krypton and argon have shown favourable performance metrics in the laboratory, however the low critical temperature of xenon makes it the only nobel gas which can be stored as a supercritical fluid at reasonable pressures in space. Solid propellants such as bismuth and iodine can be stored at densities even greater than xenon and at even lower pressures. Unfortunately, these options have generally been rejected due to back-sputtering leading to spacecraft contamination risks; which are particularly problematic for conductive propellants.[2]

We propose that a Hall Effect Thruster (HET) could be modified to operate on the hydrogen and oxygen produced in situ from the electrolysis of water. In the remainder of this paper we refer to such a system as an oxygen HET for reasons that will become clear. Such a system would benefit from the low cost of water, as well as its high storage density at low pressures. During burn times an electrolyser will operate to produce oxygen and hydrogen on demand, eliminating the need for any gas phase storage on board. Electrolysis in space has a very high TRL, with the International Space Station relying on it for astronaut life support.[3] We argue that the added mass of the electrolyser will be offset to some extent by the high pressure xenon tanks being replaced by low pressure water tanks.

Section II details the motivation behind pairing an electrolyser with an electric propulsion system. The chemical compatibility between the propellant and the neutraliser is an obvious concern. Subsection IIA addresses how traditional Lanthanum Hexaboride ($LaB_6$) cathodes can still be utilised while mitigating poisoning. Next we discuss potential performance metrics in subsection IIB. The utilisation of water electrolysis for a chemical propulsion systems have been tested in the laboratory since the 1970s, with high TRL systems expected to fly in the very near future.[4–6] We describe how an oxygen HET unlocks the potential for a single spacecraft to utilise water for a dual mode chemical-electrical propulsion architecture in subsection IIC. Subsection IID describes how the a electrolyser can be paired with a fuel cell, so that the hydrogen and oxygen produced in space can serve as both an energy storage medium as well as a propellant, paving the way for a hybridisation of the propulsion subsystem and the energy storage subsystems.

We would expect that a typical HET optimised for xenon operation would perform poorly, if at all, on the products of water electrolysis. In order to test the feasibility of such a thruster, we have designed the **W**ater **E**lec**T**rolysis **H**all **E**ffect **T**hruster, or WET-HET, which has been resized specifically for operation using oxygen. Section III describes the design procedure and results. We have developed a zero-dimensional particle-in-cell software named PlasmaSim to optimise the geometry of the WET-HET. Subsection IIIA provides details on the model and demonstrates its sensitivity with a validation test case. The physical design and thermal simulations of the WET-HET are presented in subsection IIIB. Subsection IIIC describes the magnetic model of the thruster, which we have designed to allow both the channel depth and magnetisation region to be physically adjusted in the laboratory. We find this optimised geometry considerably smaller than traditional thrusters of the same power level operationg on xenon.

# II. Motivation

Water presents itself as an attractive propellant for a HET due to it being easily stored at low pressures and high densities, yet without the chemical contamination risk associated with solid propellants. Not only is water cheap and extremely safe to handle, but the ubiquity of water throughout the solar system suggests future In Situ Resource Utilization (ISRU) potential. The ISRU of water is generally considered to be at a higher TRL level than other resources, as it has long been identified as a widespread precursor to chemical rocket propellants.[7]

## A. Cathode Poisoning

The neutraliser in an electric propulsion system is generally far more sensitive to the chemical reactivity of the propellant than the thruster itself. Oxygen has been shown to be one of the most detrimental poisons to the Lanthanum Hexaboride cathodes traditionally used with HETs.[8,9] It is shown in Ref. 8 that a $LaB_6$ cathode operated at less than 40% of nominal current at oxygen pressures as low as $10^{-5}$ Torr. The same study showed that hydrogen has the opposite effect to oxygen, acting even to counteract the poisoning effect of the cathode by a process which the author assumes to be hydrogen-ion bombardment.

Given the electrolysis of water produces hydrogen and oxygen at mass ratio of 1:8, we suggest that the anode of the thruster be operated on oxygen, whereas the neutraliser is operated on hydrogen. This would ensure that any poisoning of the $LaB_6$ cathode would be mitigated by the "de-poisoning" property of hydrogen. The mass ratio of 1:8 of $H_2$:$O_2$ is coincidentally an advantageous cathode-to-anode massflow ratio. For comparison a typical SPT100 operating on xenon generally has a cathode-to-anode ratio of between 1:30 and 1:10.[10] By utilising the stoichiometric $H_2$:$O_2$ ratio of water for a HET we eliminate the need for on-board gas storage, operating the electrolyser in conjunction with the propulsion system to generate hydrogen and oxygen as they are required. When referring to oxygen HET operation in the remainder of this paper, we assume the neutraliser to be operating on hydrogen as we consider this crucial to the feasibility of a water electrolysis HET architecture.

### B. Performance Predictions

We can use simple scaling laws to anticipate how the Thrust To Power Ratio (TTPR) and specific impulse (Isp) of an oxygen HET compares to a similar device operating on xenon in an optimistic scenario.[11] The change in atomic mass from xenon to oxygen is a reduction by a factor of 4.09, suggesting that the Isp of such a thruster could double, whereas the TTPR would be expected to halve for a similarly optimised device. For an oxygen HET operating at 1.5 kW, and at 50 sccm anode massflow, we could theoretically expect to see an Isp of up to 3200 s, and a TTPR of around 31 mN/kW.[11] This excludes the power expended to electrolyse the water, which is around 100 W at this operating point. We stress that these numbers are purely theoretically, where we assume the same propellant utilisation efficiency as xenon thrusters, and are based on basic scaling laws. The trend of doubling Isp and halving TTPR moves the performance envelope closer to what is produced by gridded ion thrusters operating on xenon, suggesting mission characteristics which could benefit from such a system already exist.

The above performance predictions assume that all $O_2$ molecules are singly ionised. In reality a fraction of $O_2$ molecules will be dissociated to two atomic oxygen species, which can subsequently be ionised and accelerated, reducing the mass of the ejected particles further. As the fraction of atomic ions to molecular ions increases the Isp will further increase at the expense of a lower TTPR. Previous simulations using a zero-dimensional kinematic Boltzmann solver suggest that the fraction of O species to $O_2$ increases with the residency time of the particles in the thruster channel, and is thus dependent on thruster geometry and anode potential.[11]

Unlike xenon, oxygen naturally forms a diatomic molecule, meaning the pair of oxygen atoms are bonded by a covalent bond. When an electron strikes an oxygen molecule, the kinetic energy of the collision can be absorbed by this bond, resulting in the two oxygen atoms vibrating or rotating in relation to one another.[12] Such an electron-molecule collision increases the internal energy of the molecule, but does not contribute to thrust generation, and is thus considered wasted. This is a method in which energy can be lost in a oxygen plasma but not a xenon plasma, due to the two added degrees of freedom of the covalent bond. The excitation of these internal degrees of freedom effectively reduces the energy of the electron population, leaving less electrons with sufficient energy to ionise the oxygen molecules.[11] Energy loss due to internal degrees of freedom of oxygen are expected to decrease the TTPR.

### C. Dual Mode Propulsion

The strongest argument for an oxygen HET propulsion system is not the high storage density or low price of the propellant, but the fact that water electrolysis is already being utilised as a chemical propellant.[4–6] Storing water as a liquid, and only producing hydrogen and oxygen through electrolysis as they are consumed presents an elegant method to benefit from the high performance of a $H_2/O_2$ system (theoretically over 450s Isp) without needing to store cryogenic gases. Such electrolysis chemical propulsion systems have been tested in the laboratory since the 1970s, with very high TRL systems expected to fly in the very near future.[4–6] These systems either operate continuously by constantly powering the electrolyser, or in a pulsed mode in which plenums are charged with gaseous $H_2$ and $O_2$ for stronger, shorter burns.

We suggest that a single spacecraft could access a very broad and rich tradespace by combining an oxygen HET with a $H_2/O_2$ chemical propulsion system. Doing so would allow a spacecraft to fly with both an electrical and chemical propulsion system, but a single propellant tank, propellant management system, and power supply. Such a dual mode system would have the ability to operate in a high Isp electric mode, or a high thrust chemical mode. The flexibility of a single propellant for high thrust and high Isp burns opens a plethora of mission scenarios that are not possible with either technology alone, yet without the mass penalty incurred by flying with two separate systems and propellants. For example:

- **LEO Constellations and On-orbit servicing:** Electric burns for drag compensation can increase lifetime, raise orbits and perform station keeping. Chemical propulsion used for proximity operations, controlled re-entry and plane changes. The safety and speed of spacecraft integration and fuelling is vastly increased when replacing traditional chemical propellants with water, reducing costs.

- **Interplanetary Exploration:** The flexibility of two vastly different propulsion systems allows drastic trajectory and mission changes even after launch. Orbital escape and orbital insertion burns benefit from high thrust chemical burns, where electric burns are useful for high delta-V cruises. Interplanetary missions using high impulse electric cruises can make use of the Oberth effect to dramatically increase the effectiveness of gravity assist manoeuvres: this is done by performing a high thrust chemical burn at lowest possible orbital periapsis within a body's gravity well, reducing gravity drag.[13] Several of the most alluring exploration targets for astrobiologist are that because of their water sources, suggesting the possibility of ISRU for refuelling.

- **Space mining:** Electric burns can be used for high delta-V transits, while high thrust chemical burns enable proximity flying, landing and takeoff. Prospecting spacecraft have already demonstrated water ISRU and high thrust propulsion in the laboratory.[7]

### D. A Unified Water System Architecture

Hydrogen-oxygen fuel cells have been utilised in space for power generation as early as the 1960s, where they flew in project Gemini.[14] Fuel cells generate water and electricity from gaseous hydrogen and oxygen, effectively working as a reverse electrolyser. A Regenerative Fuel Cell System (RFCS) combines both an electrolyser and a fuel cell into a single closed system for energy storage.[15] The system converts $H_2$ and $O_2$ into water when power is needed, and separates the same water back into $H_2$ and $O_2$ when power is available. Such a closed system can fill the energy storage role of a traditional rechargeable battery.

As telecommunication satellites grow, so do their power demands. ESA foresees these demands rising to over 30kW within the next 10 years.[16] The agency has investigated the use of RFCSs to power these spacecraft, so that they can continue their high power operation while their solar arrays are eclipsed by the Earth. These periods put the most electrical stress on the spacecraft, as enough power needs to be stored to operate the payload 72 minutes at a time.[15] Complete RFCSs, including electrolyser, fuel cell, reactants, and storage tanks, are projected to reduce system mass significantly when compared to modern lithium ion batteries, providing up to four times the energy density in ideal scenarios.[17] Experimental tests show that RFCSs have the potential to last an entire 15 year lifetime in orbit with a degradation below 0.01 U/cycle.[16]

The dramatic mass saving made available by replacing lithium batteries with a RFCS suggest that we may see water and electrolysers flying in the near future. If this is the case, further mass savings could be achieved by also using the electrolysed water for propulsion. A single water storage tank and electrolyser could be used to store energy, and supply propellant to a $H_2/O_2$ electric propellant system. This would increase the size of the water tank required, but negate the need for a separate propellant tank. The power storage system and the propulsion system are two of the heaviest subsystems on a spacecraft, so combining the two would offer substantial mass savings.

Integrating the power and propulsion subsystem of a spacecraft using electrolysis was first proposed in the 1990s.[18] The concept of a Integrated Modular Propulsion and Regenerative Electro-Energy Storage System (IMPRESS) got so far that laboratory experiments were conducted, showing that a single electrolyser could be used both for propulsion and energy storage.[19] We suggest this concept could be taken one step further, by combing the energy storage subsystem with both a chemical and an electrical propulsion system. The amalgamation of these three subsystems into one presents mass savings on the overall system architecture, yet with the vast tradespace dual mode chemical-electric propulsion can provide. This system architecture is shown in Fig. 1. Here water is electrolysed in space so that the produced $H_2$ and $O_2$ can be used in an electrical propulsion system, a chemical propulsion system, and a fuel cell energy system. The $H_2$ gas could further be used for a cold gas thrusters for attitude and orbit control, given that this gas has a theoretical

Isp of 296 s as a cold gas thruster, compared to nitrogen which has 80 s and is currently widely used. Such a highly integrated system architecture has the potential to greatly reduce spacecraft mass and increase the competitiveness of the platform.

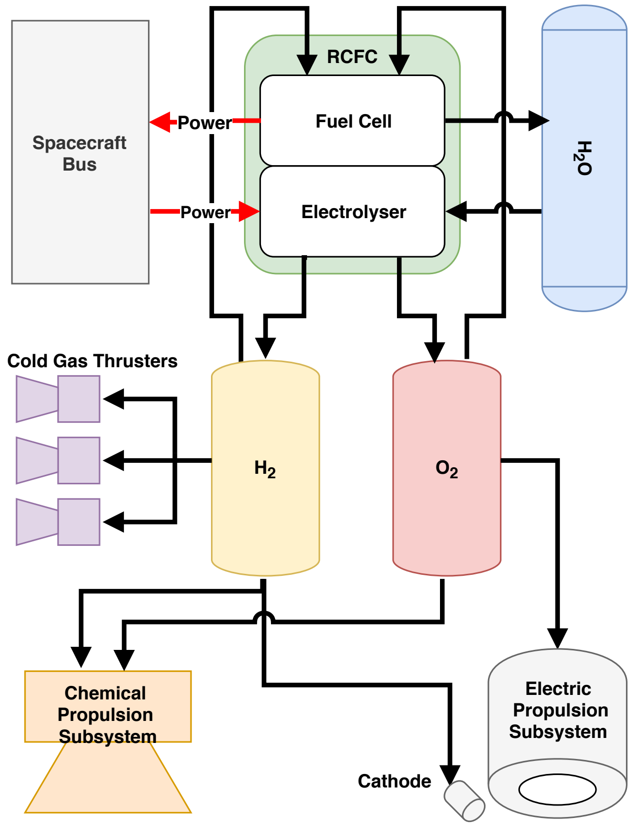


**Figure 1. A fully integrated spacecraft water system architecture. Water is electrolysed so that is can be used for the electrical propulsion system, chemical propulsion system, and fuel cell.**

We do not propose that the feasibility of an oxygen HET is contingent on dual mode chemical propulsion systems, or unified water architectures. However, as xenon prices increase even further, the electric propulsion community must diversify its propellant options. By observing trends in both the chemical propulsion field and the power storage field we predict that water, electrolysers, and their associated management systems will soon take to the skies. The development of oxygen HETs and hydrogen neutralisers allows electric propulsion subsystems to capitalise on hardware verified and validated by other communities, while simultaneously breaking an expensive xenon addiction.

## III. Thruster Optimisation for Water Electrolysis: the WET-HET

Having provided the motivation for a HET to operate on the products of water electrolysis, we present the first thruster designed to test this concept: the **W**ater **E**lec**T**rolysis **H**all **E**ffect **T**hruster, or WET-HET. The WET-HET design stems from a typical xenon HET, yet with alterations to optimise the channel dimensions and magnetic topology for oxygen ionisation. Our target operating condition, used as a starting point for the sizing was 1-2 kW and 50 sccm of oxygen anode flow. The ionisation energy of an oxygen molecule is 12.07 eV, which is very similar to that of a xenon atom at 12.13 eV, however the electron-impact ionisation cross section of oxygen is considerably smaller.[20,21] This suggests that a thruster optimised for oxygen would have a considerably different geometry than one optimised for xenon. The first step in designing the WET-HET was to determine how a typical thruster geometry would be altered when optimised for a significantly different plasma. We employed an in-house Particle-In-Cell (PIC) code named PlasmaSim, to simulate how changes in thruster geometry impact plasma properties.

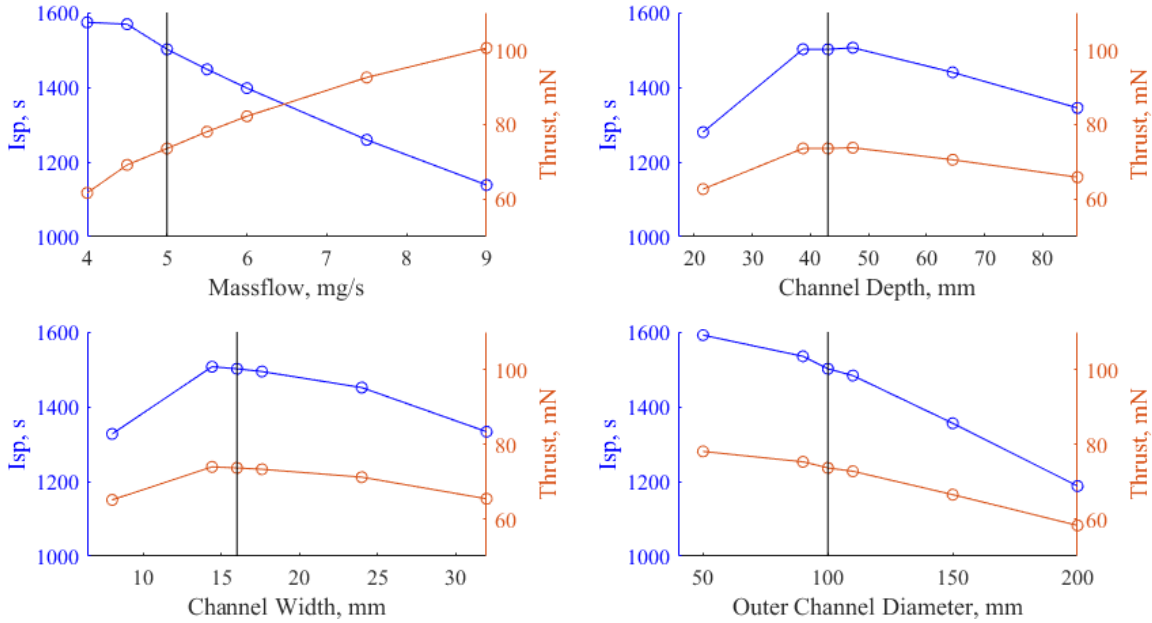


**Figure 2. PlasmaSim sensitivity analysis for an SPT100 HET at constant power. The black line represents the actual value.**

### A. Thruster Sizing using PlasmaSim

PlasmaSim is a fully kinetic simulation software developed within Imperial College London. A Boris pusher method is employed with collisions being calculated by Direct Simulation Monte Carlo. When designing the WET-HET we optimise for the following variables: anode potential, massflow, channel depth, channel width, and channel diameter. The high dimensionality of such an optimisation demands a flexible code which is fast enough to execute multiple simulations daily. We have developed a simplified version of PlasmaSim specifically for this purpose, by reducing the simulation domain to a single cell which represents the toroidal thruster channel. This code allows several milliseconds of simulation time in less than half an hour using an ordinary laptop. This quasi-zero dimensional version of PlasmaSim employs a constant electric field along the thruster axis, and neglects the magnetic field altogether, but imposes a fixed temperature on the electrons to mimic the action of Ohmic heating. Neutral particles are introduced at the anode plane. A seed electron population enters the thruster exit plane with a Maxwellian temperature distribution. Neutral particles and electrons are reflected by the channel walls, where ions recombine and return to the simulation as neutrals. The plasma is kept quasi-neutral, by removing electrons as ions recombine or leave the domain. Due to our domain having only one cell, our simulation is forced to consider the entire thruster channel to be homogeneous. This makes selecting a electron temperature difficult, as it is not representative of a real HET. In reality the electron temperature within a HET is lowest at the anode, and peaks with the magnetic field strength near the exit plane.[22]

To validate the effectiveness of PlasmaSim to optimise the channel dimensions of a HET we perform a sensitivity analysis of a thruster which we know has been optimised experimentally: the SPT100. Originally flown in 1994, the SPT100 dominates the HET market: of the 130 GEO spacecraft launched with HETs onboard between 1981 and 2018, 84 had a SPT100 onboard.[23] We run PlasmaSim at the default SPT100 dimensions and massflow. These are 5 mg/s xenon, a channel depth of 42 mm, channel width 16 mm and outer channel diameter of 100 mm.[10] For an average electron temperature we selected 11.5 eV, and set the neutral temperature to 300 K.[24] Next we independently change channel dimensions and massflow between 50% and 200% of the original value, while keeping power constant. The results are shown in Fig. 2. Increasing massflow at a constant power setting increases thrust at the expense of Isp as one would expect. For both the channel width and depth, the PlasmaSim results agree that the default size is in fact the optimal size, with both Isp and thrust dropping if either of these dimensions decrease or increase. For the channel outer diameter the PlasmaSim results suggest that both Isp and thrust could be increased if the diameter of the SPT100 was reduced. Suggestions for why this has not be implemented in the SPT100 design is either that reducing the diameter causes thermal issues, or that the central magnet requires this volume. Nevertheless, these results instill confidence that although highly simplified, PlasmaSim has the ability to determine how the dimensions of a thruster relate to both thrust and Isp.

Next we adapt PlasmaSim to operate on oxygen as opposed to xenon so that a similar optimisation for the massflow, anode potential, and geometry for the WET-HET can be obtained. Again we used a Maxwellian temperature distribution for the electrons of 11.5 eV. In reality we have little information of what the electron temperature will be in the WET-HET, so we adopted the same number as in the SPT100 validation case.

Given the high dimensionality of this optimisation problem, a high number of iterations were required before we eventually arrived at the operational points shown in table 1. Many of the WET-HET stable operational points proved considerably more temperamental than those for the SPT100, meaning that even slight deviations in one parameter resulted in unstable solutions where the plasma extinguished. The discontinuities in the Isp and thrust between similar operational points suggest result of a sensitivity analysis equivalent to that shown in Fig. 2 proved uninformative for the WET-HET, and have thus be omitted. We can see that although the thrusters have similar volumetric massflows and power, the WET-HET has a considerably narrower channel with only a quarter the radius. This results in a greater neutral density in the thruster, increasing collision probability.

| **Parameter** | **WET-HET Value** | **SPT100 Value** | **Unit** |
|---|---|---|---|
| Massflow (Gravimetric) | 1-1.5 ($O_2$) | 5 (Xe) | mg/s |
| Massflow (Volumetric) | 40-60 ($O_2$) | 50 (Xe) | sccm |
| Power | 1-1.5 | 1.35 | kW |
| Channel Depth | 35-60 | 42 | mm |
| Channel Width | 5 | 16 | mm |
| Channel Outer Diameter | 25 | 100 | mm |

**Table 1. Optimised dimensions and operational points of the WET-HET compared to that of the SPT100.**

A range of channel depths for the WET-HET produced favourable results, many of which are considerably longer than for the SPT100. A longer channel depth extends the path that a molecule must take to exit the thruster, thus increasing the neutral residency time. Previous simulations have investigated the impact that residence time has on oxygen ionisation fraction in a HET.[11] An important result being that when considering both molecular ions ($O_2^+$) and atomic ions ($O^+$), the maximum ionisation fraction is reached relatively quickly. However, beyond this maximum the ionisation rate remains constant whereas the ratio of atomic oxygen ions to molecular ions increased, e.g $O^+$:$O_2^+$. Due to the lower mass of the atomic ions, an increased ratio of atomic ions decreases thrust but increases Isp. In its current form, PlasmaSim cannot simulate dissociation, meaning the production of atomic ions is not captured. Given the strong impact that this may have on the performance of the thruster, we have thus designed the WET-HET to have a variable channel depth.

## B. Thruster Design

The final design of the thruster is shown in figure 3, accompanied by a description and materials selection list in table 2. The propellant enters the channel via the inlet tube, and disperses azimuthally as it travels axially between the anode and the inner channel wall. The flow is slightly choked by the anode cap before entering the channel. Several copper anodes of different lengths are being produced, which are easily interchangeable in the laboratory. This allows us to physically alter the channel depth, effectively controlling the residence time of neutrals within the chamber. We can thus alter the channel depth to be anywhere between 35 mm and 65 mm. The impact of residence time on performance can thereby be measured experimentally.

The WET-HET operates at power levels between 1-1.5 kW, however, PlasmaSim simulations suggest that Isp is expected to increase greatly at even higher powers. Conservative thermal simulations using the thermal analysis suit in Finite Element Method Magnetics (FEMM) have been performed to ensure the thruster can operate within the thermal limits of the materials selected.[25] Results of the thermal analysis at 1 kW are shown in Fig. 4.

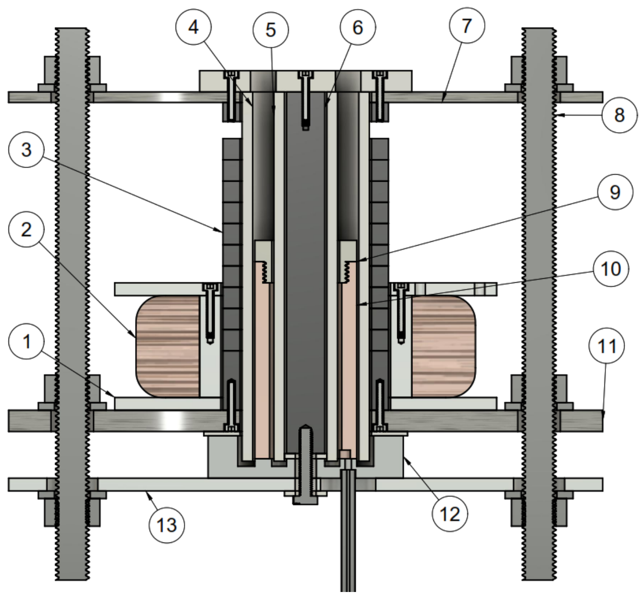


Figure 3. Cross section design of the WET-HET

| No. | Name | Material |
|---|---|---|
| 1 | Coil reel | Aluminium |
| 2 | Magnet coil | Copper |
| 3 | Outer pole stack | Soft Iron |
| 4 | Outer channel wall | Alumina |
| 5 | Inner channel wall | Alumina |
| 6 | Inner pole | Soft Iron |
| 7 | Front plate | Stainless steel |
| 8 | Threaded rod structure | Stainless steel |
| 9 | Anode cap | Tungsten |
| 10 | Anode | Copper |
| 11 | Back plate | Stainless steel |
| 12 | Tail cap | Stainless steel |
| 13 | Radiator | Aluminium |

Table 2. Material Selection

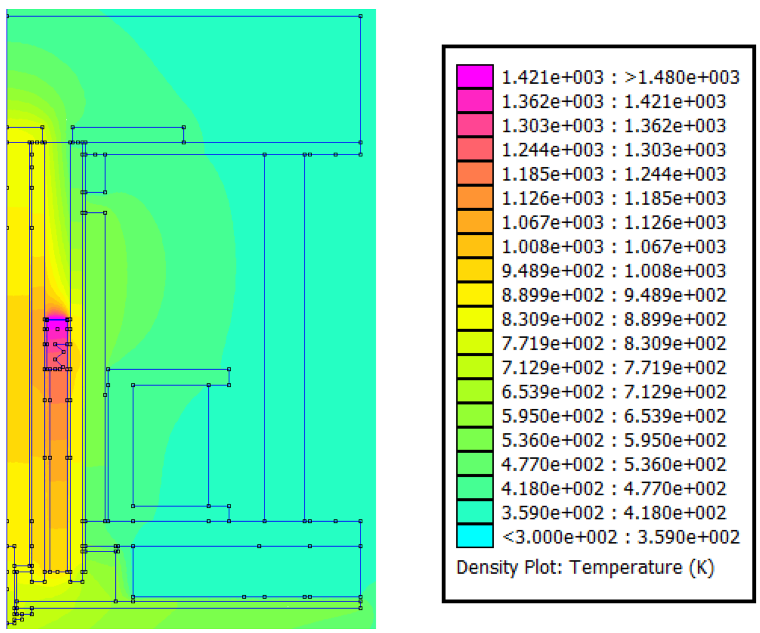


**Figure 4. Axisymmetric thermal simulation of the WET-HET operating at 1 kW. The axis of symmetry is on the left hand side**

Thermal management proved to be a key challenge for this design, due to the relatively small size for a thruster of this power class. We model a very conservative worst possible scenario, where the entire input energy is deposited on the anode face. We have chosen a copper anode to efficiently conduct this heat towards the rear stainless steel tail cap of the thruster, to which the anode is in very good thermal contact. A large aluminium radiator, treated with a high emissivity coating is employed to dissipate heat from the tail cap to the surroundings. The anode cap sits at the top of the anode and must withstand the greatest heating. The temperatures that the anode cap will reach are outside of the operating temperature of copper. For this reason we have chosen this cap to be constructed from tungsten.

### C. Magnetic Design

For typical xenon HETs the magnetic field crosses the thruster channel only near the exit plane of the thruster. In the region where the radial magnetic field overlaps with the axial electric field, the electrons are magnetised. The magnetised electrons are diverted, and confined to flow orthogonally to both fields, resulting in the azimuthal Hall current. The increased electron density in the magnetised region ultimately results in the majority of ionisation being localised in the region between the magnetic poles.

Due to the lower ionisation cross section of molecular oxygen when compared to xenon, we expect fewer neutrals to become ionised within the magnetised region, reducing propellant utilisation and consequentially Isp. The WET-HET combats this by extending the radial magnetic field, and thus extending the magnetised region further into the channel. This serves to increase the Hall current depth, extending the region of high electron density, and ultimately increasing the likelihood of a electron-neutral collision.

By increasing the magnetised length too greatly we risk reduction of the acceleration region of the channel, potentially sacrificing ion velocity in lieu of a greater propellant utilisation fraction. As with the channel depth, the ideal magnetisation region length cannot be determined with our zero dimensional model, and therefore will need to be established experimentally. The WET-HET has been designed to allow the manipulation of the magnetic topology within the laboratory. We see the thruster in its default configuration in Fig. 5a, with minimal channel depth and minimal magnetisation region. The right of Fig. 5a shows the magnetic field density and field lines for this configuration, using the magnetostatic suit of FEMM.[25] The outer magnetic pole comprises a stack of soft iron rings indicated by number 3 in Fig. 3. The missing iron ring or “notch” determines the separation between magnetic poles: above the notch the magnetic field lines lie radially, increasing the Hall current and thus magnetisation depth. By moving these rings upwards or downwards, we have the ability to manually increase or decrease the magnetic field thickness. This can be seen in Fig. 5b. Here we have replaced the copper anode for a shorter one to maximise the channel depth, as well as raising all outer pole rings to give the maximum magnetisation region thickness. The resulting magnetic field is shown to the right, with the entire channel length being magnetised. Fig. 5 shows the two extremes in configuration of both channel depth and magnetisation region depth, but configurations between these extremes will also be tested.

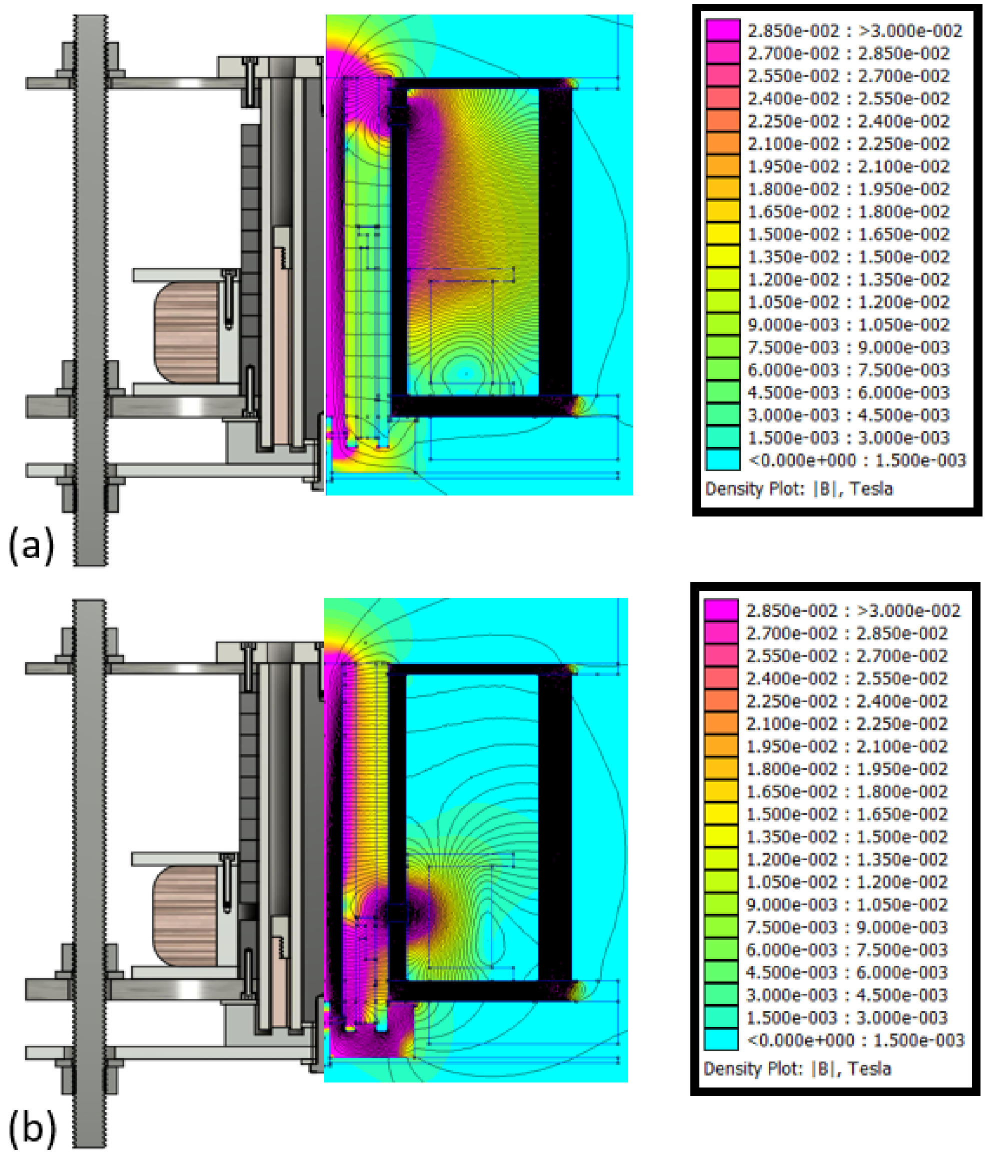


**Figure 5. The WET-HET showing different magnetic field configurations, with superposition of magnetic modelling. The configurations in 5a shows minimum magnetisation region with all rings in the downward position. The configuration in 5b shows all rings in the raised position, producing the longest possible magnetisation region. Note that in 5b a smaller anode has been installed, increasing the channel depth to the maximum.**

## IV. Conclusion

We have presented the motivation for designing a thruster to operate on the products of water electrolysis. Not only does such a thruster benefit from the high storability, low price, and low toxicity of water, but electrolysed water has been shown extremely effective as a chemical propellant. By operating the anode on the oxygen, and neutraliser on the hydrogen generated by electrolysis, we suggest the poisoning of the cathode can be effectively mitigated. Such a system would allow water and an electrolyser to feed propellant to both a high impulse electrical propulsion system and a high thrust chemical propulsion system while suffering lower mass penalty than two independent propulsion systems. Such a chemical-electrical dual mode propulsion architecture paves the way to a very broad and exciting tradespace. The benefit of this subsystem hybridisation can be pushed further still by replacing energy storing batteries with fuel cells, combing propulsion and energy storage into a single system. The WET-HET has been designed to operate on the products of water electrolysis. We have used a zero-dimensional particle in cell software named PlasmaSim to optimise the geometry and operating point. When compared to a xenon thruster, the WET-

HET has a deeper channel and smaller diameter than a xenon thruster in a similar power class. Due to limitations of the plasma model used, uncertainties on the optimal channel depth and magnetisation region length still exist. The WET-HET thruster design allows both of these parameters to be altered in the laboratory, so that the optimal value can be determined experimentally. Thermal modelling has ensured that the thruster operates within the physical limits of the materials selected. With thruster manufacturing currently underway, we expect direct thrust measurements to follow shortly.

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