Experimental Investigation of a Water Electrolysis Hall Effect Thruster

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ABSTRACT

We conceptualise an electric propulsion system in which water is utilised as a propellant for a Hall effect thruster using in situ electrolysis. By supplying the generated oxygen to the thruster anode and the hydrogen to the neutralising cathode, poisoning of the cathode emitters is mitigated. Not only does such a system benefit from the low cost, high storability and in situ resource utilisation potential of water, but synergies with water electrolysis chemical propulsion systems allow for multi-mode chemical-electrical propulsion architectures. The water electrolysis Hall effect thruster (WET-HET) has been optimised to operate on oxygen as a proof of this concept. We perform direct thrust measurements on the WET-HET using a hanging pendulum thrust balance. The thruster was operated using oxygen mass flow rates ranging from 0.96 mgs^{-1} to 1.85 mgs^{-1}, and discharge powers ranging from 490 W to 2880 W. The cathode used in this test was supplied with krypton rather than hydrogen, due to laboratory restrictions preventing compressed hydrogen and oxygen cylinders being used in close proximity. Two channel wall materials were investigated - alumina and boron nitride. It was found that the wall material had a significant impact on the thrust, with an increase of approximately 40% for boron nitride. Reconfiguration of the magnetic components of the WET-HET allows us to alter the thickness of the magnetised region within the thruster channel. We test the device in three different magnetic configurations, ranging from a traditionally thin magnetic region to complete magnetisation of the discharge channel. We find that increasing the thickness of the magnetic region reduces thrust, specific impulse, and thrust efficiency of the device. We assess the change in performance as we change the discharge channel depth of the thruster. The best performance was achieved with the shallowest channel of depth 35 mm. We find the that thrust, specific impulse and anode thrust efficiency increases linearly with power for all configurations with no obvious plateau. Greatest specific impulse and efficiency was found found when mass flow was lowest. Although discharge current increases linearly with magnetic field strength, thrust, specific impulse and efficiency peaks at 480 Gauss. The greatest thrust measured was 38.63±0.25 mN, with a maximum specific impulse of 4112±36 s and a maximum anode thrust efficiency of 15.50±0.27%.

1. Overview

We present thrust measurements of the Water Electrolysis Hall Effect Thruster (WET-HET) which has been specifically modified to operate on the products of water electrolysis. These results build on previous measurements of the WET-HET published by Schwertheim and Knoll [30, 32], with the same thruster and experimental set-up. What differs in this study is that the discharge channel of the thruster has been modified, leading to a substantial performance increase. We also test the thruster at higher powers and with three different magnetic field topologies to analyse how this impacts thrust generation. Finally we change the depth of the discharge channel to assess how the impacts performance. We describe the demand for alternative propellants for electric propulsion, and the benefits that water can offer in section 2. We present the design of the WET-HET device in section 3, and describe the experimental set-up in section 4. Result are presented and discussed in sections 5 and 6. The conclusion of this study are summarised in section 7.

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2. Background

2.1. Alternative Propellants

With very few exceptions, xenon has dominated the electric propulsion (EP) market as the de facto standard propellant for the two most flown plasma propulsion technologies: gridded ion engines (GIEs) and Hall effect thrusters (HETs). Xenon is easily ionized due to it having a large electron-impact ionisation cross section and a relatively low first energy of ionization. Xenon is chemically inert and can be stored at high densities as a supercritical fluid without the need for heavy cryogenics. A major drawback of utilizing xenon as an electric propellant is its high price, which has been proven to fluctuate greatly: the price of xenon increased by a factor of ten in less than eight years, such that a kilogram of high purity xenon currently costs several thousands of euros [37]. The growing cost of the xenon is not yet great enough to deter large prime contractors, yet high power EP systems will require tens of millions of euros worth of xenon at today's prices, which are themselves highly dependent on demand [37]. Moreover, for small companies and start-ups trying to break into the EP market, the xenon required even for development and ground testing presents a very expensive hurdle on the path to thruster qualification. Although xenon is generally considered a green propellant, the vast amounts of energy required to separate xenon from the atmosphere produces a very large carbon footprint [29]. The extreme cost of xenon is now driving many to search for alternative propellants.

Like xenon, the ideal alternative propellant for EP should have a low energy of ionisation and a large electron-impact ionization cross section. The search is generally restricted to monatomic or diatomic elements in a bid to reduce the number of covalent bonds in the propellant. The propellant is ionized via electron impact, so each covalent bond has the potential to absorb and store the kinetic energy of a colliding electron as rotational or vibrational potential [22]. This energy presents work done by the thruster that does not directly contribute to thrust and is therefore considered to be lost. On a system level an alternative propellant must be cheaper than xenon, be storable at high densities and not chemically react to deteriorate the thruster, cathode, or spacecraft itself.

Both HET and GIE systems depend on the continuous operation of a cathode to supply the thruster with electrons. The most commonly flown cathodes for EP missions are hollow cathodes, which are particularly constraining on potential alternative propellants. In a hollow cathode, a low work-function thermionic emitter is heated in the presence of a chemically inert gas. Once the operational temperature is reached an electron current can be drawn out of the emitter surface [14].

In a typical EP mission, the working gas in the hollow cathode is xenon flowing at approximately 5-10% of the total mass flow rate, with the remaining mass flow going to the thruster anode. For these applications, the low work-function thermionic emitters used are either made of lanthanum hexaboride (LaB_6) or a barium oxide impregnated tungsten matrix [14]. These emitters are notoriously sensitive to reactive gases. Traces as low as 10 ppm of air, oxygen or water in the xenon supply can chemically react with the emitters in a range of processes collectively referred to as “poisoning” [2, 10]. A poisoned cathode will produce a lower electron current until it can no longer sustain the discharge, rendering the entire EP system useless. The extreme chemical sensitivity of the emitters within the cathode dictates that only the highest purity of xenon is suitable for EP use. This also greatly restricts the search for alternative propellants as we can only consider those gases which do not poison cathodes. Out of the two emitter materials, LaB_6 has been found to be more resistant to poisoning, however, even LaB_6 cathodes have only proven to be compatible with Nobel gases and hydrogen [2, 10].

Krypton has long been identified as the most viable alternative propellant to xenon. Krypton is the next heaviest Nobel gas after xenon and shares a similar electron-impact cross section, first ionisation energy, and chemical inertness but at a considerably lower price. These similarities allow many thrusters and cathodes which were designed for xenon to operate easily on krypton, with largely similar results [23]. The only caveat of krypton is that it has a significantly lower density when stored at temperatures and pressures typical of EP missions: $0.53\,\mathrm{gcm^{-3}}$ for krypton compared to $1.6\,\mathrm{gcm^{-3}}$ for xenon at 50ºC and 14 Mpa [38]. There is therefore a system level trade-off in terms of the mass and volume penalty of the propellant tanks for high delta-V missions. SpaceX were the first to fly krypton HETs on their Starlink mega-constellation in 2019. This is due most probably to the high cost of supplying a mega-constellation with xenon, the moderate delta-V requirement of each individual spacecraft, and the company’s plans to replace each satellite frequently.

Iodine is another great contender for the next widely adopted EP propellant [41]. Iodine can be stored as a solid with a very attractive density of $4.9\,\mathrm{gcm^{-3}}$. The electron-impact cross section of iodine is similar to that of xenon and it has a lower first energy of ionization [20]. A great concern about utilizing iodine is that some of it will condense onto spacecraft surfaces. Such condensation has been shown to aggressively corrode many of the materials that make up spacecraft including stainless steels, aluminium, and titanium [25, 4]. Furthermore, hollow cathodes have only been operated on iodine for short periods of time, suggesting the necessity for novel cathode development [4, 40].

2.2. Water Electrolysis as a Propellant

It is important to note that only 5-10% of the propellant used in an EP mission is supplied to the neutralising cathode, so only this portion of the propellant needs to meet the stringent chemical requirements of the hollow cathode. We therefore suggest that hydrogen, produced through water electrolysis, can be used as the working gas for the hollow cathode. Water itself will poison hollow cathodes, however, the hydrogen that makes up 11.1% of water by mass does not [13, 36]. In a water electrolysis HET the oxygen is used for the thruster anode and the hydrogen is used to operate the cathode. Gallagher [10] tested the susceptibility of LaB_6 cathodes to poisoning when operating on a range of different gases including hydrogen. Gallagher found that hydrogen did not poison the cathode and furthermore, counteracted any poisoning of the cathode by a mechanism that was assumed to be hydrogen ion bombardment [10]. In the context of the proposed water electrolysis HET, the thruster operates on oxygen, a gas which is considered a poison to most cathodes, however, the cathode is supplied with hydrogen, which is not only coincidentally produced at near the perfect rate, but can potentially counteract oxygen contamination during extended operation.

The hydrogen produced by water electrolysis could potentially contain water in low concentrations, which could lead to cathode poisoning. This is an important consideration when selecting the electrolyser configuration and operational pressure, and may further require the use of desiccant beds to dry the supply gases [9]. Lanthanum hexaboride cathodes have a greater tolerance to water than comparable electron sources, with reports found in the literature of these devices making full recoveries after being accidentally exposed to water during operation [12, 15]. The lifetime of a LaB_6 cathode operating on hydrogen generated by an electrolyser must therefore be tested experimentally. Gas dryers based on desiccant beds have been conservatively estimated to add a mass penalty of 2% to the propellant mass [16].

A water electrolysis HET benefits from the very low cost of water which can be stored at moderate density and at low pressure. Electrolysis produces gaseous oxygen and hydrogen as they are consumed, eliminating the need for gas storage altogether. The lack of any pressurised gases makes this an attractive option both by reducing the mass penalty associated with the propellant tanks, and for rideshare missions which require passivated spacecraft.

Water has proven itself to be surprisingly ubiquitous throughout our solar system: presenting itself on mars, asteroids, and even our own moon. Many have identified water as a valuable material that can be harvested through in situ resource utilization (ISRU). Not only is water essential for life support, but it can serve as a precursor for chemical rocket propellants. The combination of these factors has driven the technology readiness level (TRL) of water ISRU to greatly outpace that of other resources [44]. A water electrolysis HET system could someday greatly benefit from these advances by refuelling on extra-terrestrial water.

The technology needed to support water electrolysis in space is already at a very high TRL, with the ISS relying on it to produce oxygen for astronauts [7]. An electrolyser requires energy to dissociate water into its constituent elements, which is an energy cost not present in a typical xenon HET. The discharge of a typical HET operating on 50 sccm of xenon draws 1.35 kW of power from the spacecraft bus [28]. For an electrolyser to produce 50 sccm of oxygen, it requires around 30 W of power, assuming a conservative electrolyser efficiency of 80% [26]. This suggests less than 3% additional power must be expended to generate sufficient propellant for a water electrolysis HET when compared to a traditional xenon system. This negligible power draw allows the HET and electrolyser to operate continuously, meaning gaseous hydrogen and oxygen are produced as they are consumed.

Perhaps the strongest argument for a water electrolysis HET is that water electrolysis is already being utilised as a propellant by the chemical propulsion community [26, 6, 19]. Designing chemical in-space propulsion systems using water electrolysis provides a very green, high performance substitute to toxic chemicals like hydrazine. We propose the combination of a water electrolysis HET with a water electrolysis chemical propulsion system on a single spacecraft; this presents an exciting opportunity of a multi-modal chemical-electrical propulsion system sharing a common propellant. This is shown schematically in figure 1. Liquid water is stored in a low pressure tank during launch. In space an electrolyser is used to dissociate a small fraction of the water into gaseous hydrogen and oxygen, which are temporarily stored in small plenums. The hydrogen and oxygen can either be used by the chemical propulsion subsystem to perform high thrust manoeuvres, or by the HET and cathode for high specific impulse (I_{sp}) manoeuvres. By utilising the same propellant, the two subsystems can share a single storage tank, electrolyser, and propellant management system. This greatly reduces the mass penalty incurred by flying two propulsion systems [27]. It is important to note that certain propellant management components are required to supply both chemical and electrical propulsion systems, and the implementation will be very different between the two. Electric propulsion systems typically operating at much lower mass flow rates than chemical propulsion systems, and at a fixed mass flow rate. Chemical propulsion systems on the other hand, generally require the propellant to be supplied at high pressure, where the pressure level itself governs the mass flow rate to the thruster. While two separate propellant management systems will be needed to support the proposed multi-mode propulsion architecture, the commonality of the propellant tank and electrolyser are expected to reduce the overall mass compared to a satellite with separate electric propulsion and chemical propulsion systems.

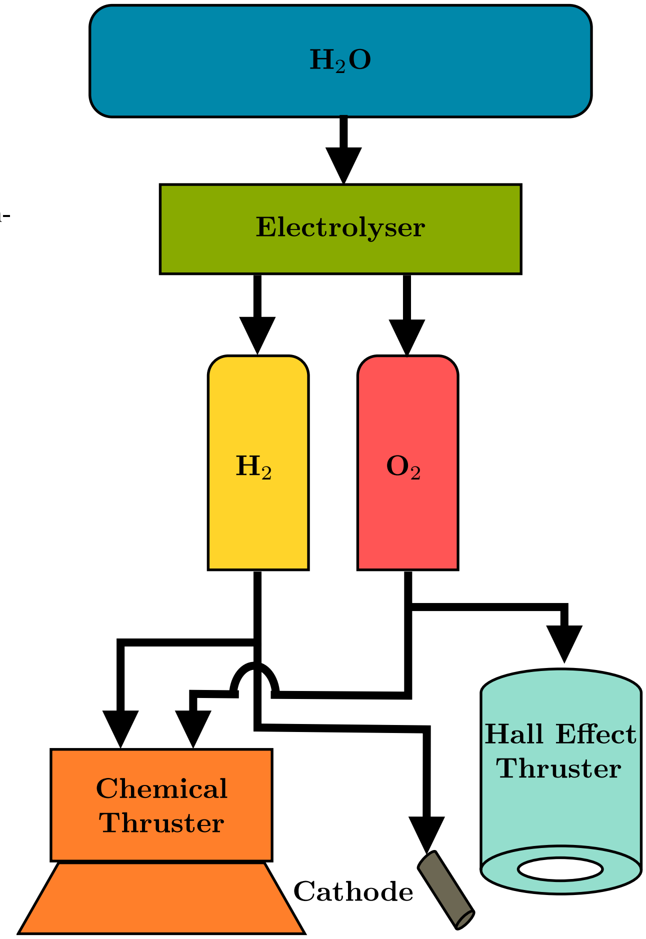

Figure 1: Schematic representation of a multi-modal chemical-electrical propulsion architecture using water as a shared propellant

A spacecraft with both chemical and electrical propulsion capabilities can perform a range of exciting trajectories that are not possible with one propulsion system alone. For example, an interplanetary mission could perform a high thrust chemical burn to escape Earth's gravity, then perform a high impulse electric cruise in interplanetary space, before finally using the chemical propulsion system for an orbital insertion burn. This "best of both worlds" architecture allows a spacecraft to use the chemical propulsion system for Hohmann transfers and plane changes, but an electric propulsion system for electric orbit raising, long duration

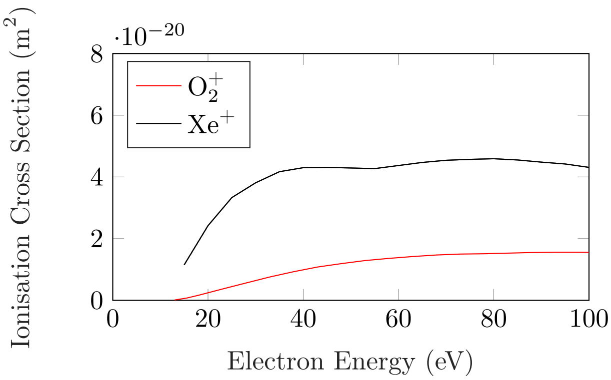

Figure 2: The electron-impact ionisation cross section of oxygen and xenon as a function of electron temperature. Taken from Itikawa [17] and Stephan and Märk [35].

low thrust manoeuvres and station keeping. Sharing a propellant between a chemical and an electrical propulsion system on a single spacecraft provides an unmatched flexibility to switch between the two propulsion modes even after launch. This is extremely advantageous to missions where the trajectory could change in flight [27]. For example, on an on-orbit servicing spacecraft which maintains a mega-constellation. Such a vehicle requires the means to reach any spacecraft that may fail, which could necessitate a combination of plane change and orbit raising/lowering manoeuvres.

As with any electric propellant, a water electrolysis HET will have some downsides. On the system level, liquid water is 1.6 times less dense than supercritical xenon, meaning larger tanks are needed for the same mass of propellant, even if they need not be pressurized. Oxygen plasmas are known to be highly aggressive, and are used industrially to etch surfaces and remove chemical contaminates. For a HET, this aggression could lead to accelerated erosion of the components in contact with the plasma, namely the ceramic discharge channel and the anode. If such a thruster were to fly, special consideration must be taken in the anode material selection, as most metals will oxidise in sustained contact with oxygen, particularly when heated.

The electron-impact cross section of oxygen is considerably lower than that of xenon at a given electron temperature, as shown in figure 2. We see that even if an oxygen HET is able to generate a considerably greater electron temperature than a traditional xenon HET, the cross section of oxygen is still far smaller and we should expect a lower propellant ionisation fraction. In addition to having a smaller cross section, the presence of the covalent bonds of the oxygen molecule will soak up a portion of the electron kinetic energy, leading to more energy lost, ultimately reducing the thrust efficiency of the thruster. For these reasons we cannot expect a water electrolysis HET to be able to compete against a comparable xenon system based on thrust, I_{sp} and thrust efficiency alone. The reduction in performance must be weighed against the additional system level benefits such as synergy with a chemical propulsion system, ISRU potential, and price.

Chemical propulsion systems that operate on water electrolysis have been demonstrated in the laboratory with great success [6, 19, 26]. Hollow cathodes operating on hydrogen have shown strong potential [13, 36]. This leaves the oxygen HET as the only unproven technology requiring further experimental investigation to establish the performance capabilities of such an architecture.

3. The Water Electrolysis Hall Effect Thruster

Oxygen molecules and xenon atoms have vastly different masses, electron-impact cross sections, and internal energy states. With very few exceptions, all HETs have been optimised to operate on xenon, and are therefore expected to operate poorly, if at all, on oxygen. In order to establish the capabilities of this technology the basic geometric parameters and magnetic topology need to be revisited in the context of an oxygen fuelled HET. The Water Electrolysis Hall Effect Thruster (WET-HET) has been designed to operate on 1-2 mgs^{-1} of oxygen, at nominal discharge powers up to 2 kW. The WET-HET is shown in figure 3, along with a cross sectional view. The channel dimensions of the WET-HET were optimised for oxygen operation using a zero-dimensional version of the in-house developed particle-in-cell simulation called PlasmaSim. A simplified zero-dimensional version of PlasmaSim was required such that hundreds of configurations could be simulated to optimise for mass flow rate, power level, and channel width, depth and circumference. This is further described in detail in Schwertheim and Knoll [33]. Optimising a thruster for oxygen lead to a considerably smaller channel cross section than a traditional device optimised for xenon: the channel of the WET-HET has an outer diameter of 25 mm and a width of 5 mm. When compared to an SPT-100 xenon thruster, the WET-HET channel is a third as wide, and a quarter the circumference [28]. The channel depth of the WET-HET can be altered. The SPT-100 and the WET-HET operate on a mass flow rate of 40-60 sccm, yet the cross section of the WET-HET channel is smaller by a factor of 13.5, which dictates that the neutral density is considerably higher. The WET-HET has an increased neutral density, a deeper discharge channel, and an exotic magnetic field topology (see below) in comparison to a traditional xenon thruster. All these features are intended to combat the lower ionisation efficiency which is expected from operating on a low mass propellant which has a small cross section and a covalent bond.

A special feature of the WET-HET not shared by other thrusters is that the copper anode (red section in figure 3) can be substituted for longer or shorter sections, effectively decreasing or increasing the depth of the discharge channel. The channel depth influences the time that neutral molecules and ions reside within discharge region before exiting into the plume. Since the timescale for molecular dissociation exceeds single ionisation for oxygen, tuning of the discharge channel depth was expected to influence the ratio of O^+ and O_2^+ ions within the discharge which is expected to have an effect on thrust, I_{sp}, and thrust efficiency [31].

The magnetic field of the WET-HET is generated by a

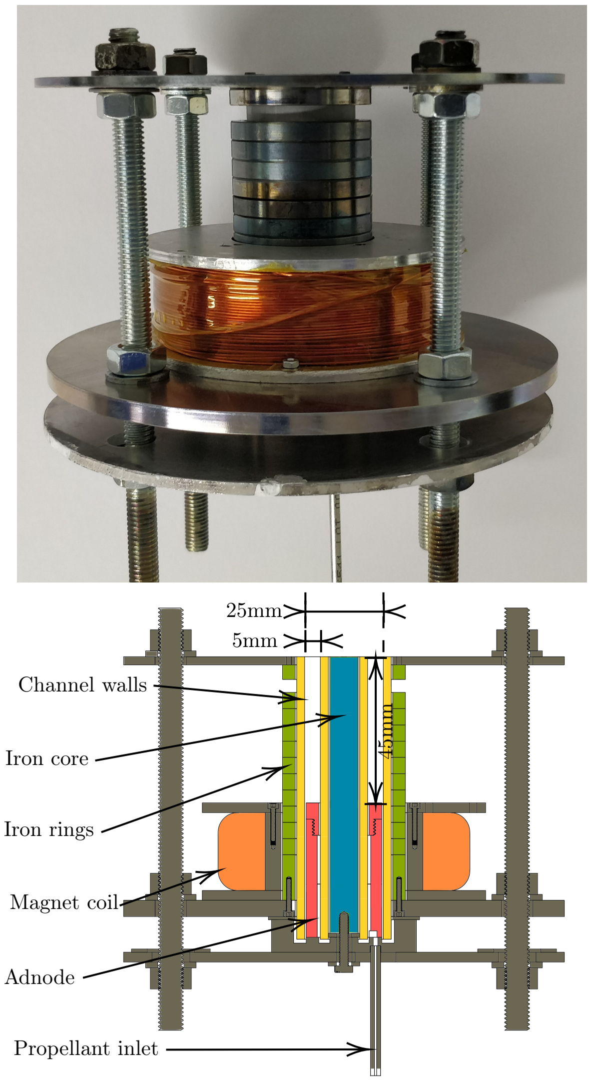

Figure 3: The Water Electrolysis Hall Effect Thruster (top) with cross section (bottom) showing main components and dimensions.

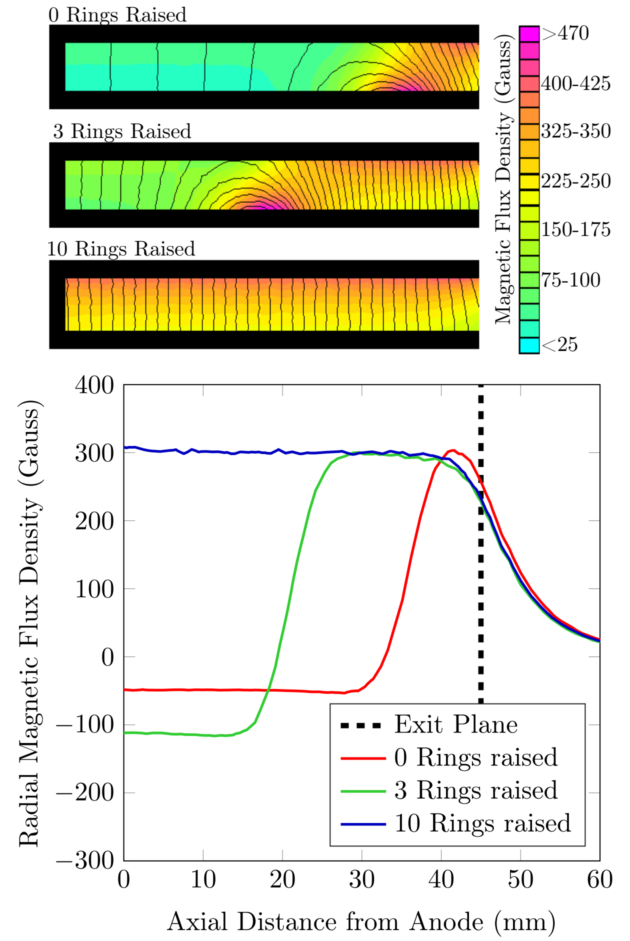

Figure 4: FEMM simulations of the magnetic flux density for three different magnetic topologies for the 45 mm deep discharge channel. The field lines and flux density are shown graphically (top), as well as a plot of the radial component of the flux density along the centre of the channel (bottom). The magnetic current has been adjusted to match maximum flux density.

single copper coil, with the soft-iron poles inside and outside serving to shape this field. The outer pole (green section in figure 3) comprises a stack of 10 rings. These rings can be moved axially up and down the thruster axis, which dramatically changes the magnetic topology within the thruster channel. Having zero rings raised is the default position, which is that shown in figure 3. Figure 4 shows three of the ten possible magnetic typologies which can be generated. These data were generated using magnetic field simulations conducted in Finite Element Method Magnetics (FEMM). Each ring that is raised increases the axial depth (as measured from the exit plane) of the radial component of the magnetic field. This broadens the magnetic region of the channel. Oxygen is a novel propellant, and has a considerably smaller electron-impact ionisation cross section than traditional propellants. The motivation for increasing the magnetic thickness was to increase the fraction of the channel containing the Hall current, so that the region of increased plasma density is spread over a larger portion of the channel. This thicker region serves to subject the neutral oxygen molecules to spending a longer duration within the ionisation region of the channel, with the ultimate goal of increasing ionisation. This was implemented as a way to combat the predictably poor ionisation fraction expected of oxygen in comparison with xenon. These motivations appear to be in line with other studies who aim to operate HETs on molecular propellants. Marchioni and Cappelli [24] have developed the Extended Channel Hall Thruster (ECHT) with the intention of operating on nitrogen and oxygen for a RAM-EP system. Both the WET-HET and the ECHT aim to increase the ionisation of molecular propellants by counteracting lower ionisation cross section and residence time of the neutrals by increasing channel length and magnetic depth.

4. Experimental Setup

The purpose of this test campaign was to perform direct thrust measurements of the WET-HET using a hanging pendulum thrust balance. Previous studies have tested this thruster at low powers, at a single magnetic configuration and channel depth [30, 32]. We present results in which the ceramic wall material of the thruster has been changed from alumina to boron nitride and the thruster is tested to a higher power. We also experimentally determine the impact of changing the magnetic topology of the thruster, and changing the discharge channel depth.

4.1. Alterations to the WET-HET

The ceramics wall material in the original thruster (yellow section in figure 3) consisted of alumina (Al_2O_2). For this test both walls were replaces with identical components made of boron nitride (BN). This was done due to concerns that the alumina may be conducting current and providing an alternative path for the electrons across the magnetic field, given the conductivity of alumina rises at high temperatures (>1400°C) in the presence of oxygen [21, 42, 32].

In previous test campaigns, only one magnetic topology was tested, namely the 0 rings raised position. This is the first campaign to alter the magnetic topology of the thruster. The three different topologies shown in figure 4 were tested namely the 0, 3 and 10 rings raised. The 0 rings raised configuration allows us to operate the WET-HET with a traditionally thin magnetic region near the channel exit. With three rings raised we have a thicker magnetic region near the exit, and ten rings raised generates a magnetic region so thick that it envelops the entire channel volume. The WET-HET has been specifically designed such that exotic magnetic typologies like those shown in figure 4 can be tested, so see whether they are effective at increasing performance with a propellant which is more difficult to ionise. This is explained in more detail within Schwertheim and Knoll [33].

By replacing the anode of the thruster with longer and shorter components we can change the physical depth of the thruster. Previous tests have tested the WET-HET at channel depths of 45 mm. Here we test the thruster at channel depths of 35 mm, 45 mm and 60mm [30, 32]. It is important to note that the magnetic topology and the channel depth can be changed completely independently of one another: the magnetic field does not change with respect to the channel exit plane.

4.2. Neutralising Cathode

For this test zero grade oxygen was directly supplied from a cylinder to the anode in place of an electrolyser. The thruster and cathode flow rates were controlled using two Bronkhorst mass flow controllers. The cathode used was a filament plasma bridge neutralizer [43]. The cathode was operated on 15 sccm of research grade krypton for all measurements. While ultimately we wish to test the WET-HET with a LaB_6 cathode operating on hydrogen, we were unable to do so for this test due to health and safety concerns of operating compressed hydrogen and oxygen in close proximity, however, future tests will include a LaB_6 cathode operating on hydrogen.

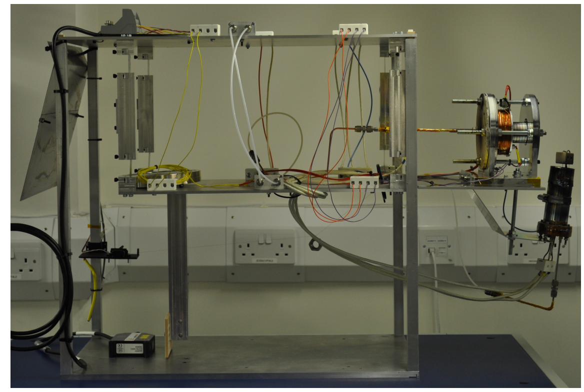

Figure 5: Side view of thrust balance with thruster and cathode attached.

4.3. Thrust Balance

A hanging pendulum type thrust balance was used, consisting of a stationary base and a top platform from which a moving central platform is suspended. The platform is hung using four parallel linkages, each containing two stainless steel fixtures. The balance is shown in figure 5. A laser sensor measures the displacement of the central platform from a resting position when subject to thrust. The laser used was a Micro-Epsilon triangulation laser sensor with an accuracy better than 0.6μm. The sensitivity of the thrust balance describes the relationship of the measured displacement in response to a force. This sensitivity is experimentally measured using a series of non-contact known forces generated by a voice coil actuator. This actuator has itself been characterised by an independently calibrated microbalance, to ensure calibration traceability. Throughout the test the calibration is monitored for stability using a servo motor and pulley system. The thrust balance design, operation, post-processing procedure and error propagation is described in detail in Schwertheim et al. [34].

4.4. Vacuum Facility

The WET-HET was tested in the Boltzmann vacuum facility of the Imperial Plasma Propulsion Laboratory (IPPL). The balance and thruster within the facility is shown in figure 6. This facility comprises a 1.5 m diameter by 2 m long main chamber and a 0.75 m diameter by 1.5 m long load-lock hatch. These chambers are pumped by a roughing pump, two Leybold turbomolecular pumps each with a pumping speed of 2200 L/s and a Leybold cryopanel at 15,000 L/s xenon.

5. Results

The WET-HET firing at 500 W with a mass flow rate of 1.32 mgs^{-1} is shown in figure 7. The thruster ignites easily on pure oxygen and generally operates with high stability. Once a discharge is established we operate the device in current controlled mode. For discharge powers above ap-

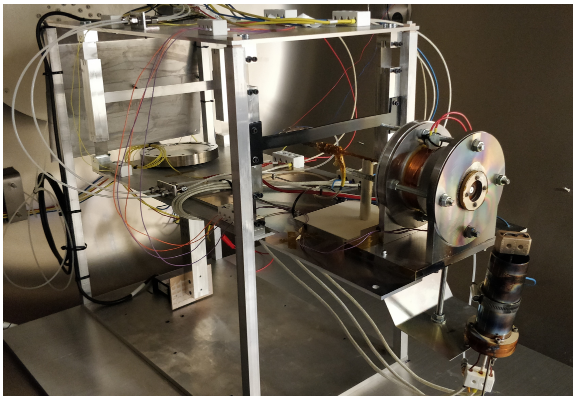

Figure 6: The WET-HET with cathode fixed to the thrust balance within the main chamber of the Boltzmann vacuum facility.

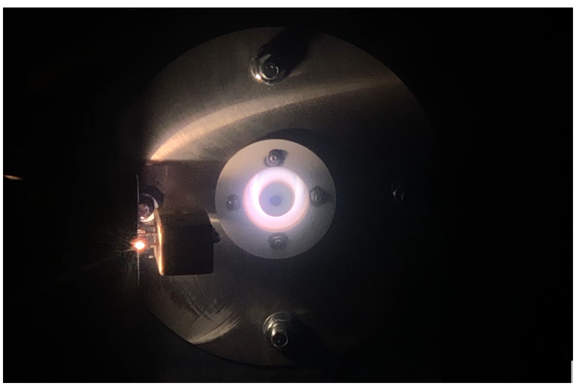

Figure 7: The WET-HET operating at 500 W. Please not that the position of the cathode is different here to the rest of the paper, but was changed to that shown in figure 6 before any measurements were taken.

proximately 1500 W, or magnetic field strengths above 500 Gauss, the thruster can only be operated for short periods due to thermal issues.

5.1. Power Dependence

The thrust, I_{sp}, anode thrust efficiency and discharge voltage of the WET-HET as a function of power are shown in figure 8. Here we define anode thrust efficiency η_T as:

$$\eta_T = \frac{T^2}{2\dot{m}P_d} \quad (1)$$

where T is thrust, $\dot{m}$ is the anode mass flow rate and P_d is the discharge power. All data in figure 8 were taken with 1.5 A of current passing through the magnet coil, and a channel depth of 45 mm. We can see that changing the discharge channel walls from Al_2O_3 to BN resulted in a thrust increase of approximately 40%. This dramatic increase in thrust was also reflected in a greater I_{sp} and efficiency at a given discharge power with the new channel material. We see that the alumina thruster requires a lower discharge voltage to sustain a given discharge current when compared to the boron nitride. It follows that at a given power the alumina has lower performance due to a lower voltage, which provides less acceleration to the ions.

It was found that the highest thruster performance was achieved with the 0 rings configuration which corresponds to the thinnest magnetic field. Contrary to expectation, increasing the magnetic depth led to a decrease in discharge voltage at a given current. This decrease in voltage is presumed to be one of the factors that leads to a lower thrust, I_{sp} and efficiency at a given discharge power.

Over the power range surveyed, all trends shown in figure 8 show a linear performance increasing with power, with no obvious plateau observed. This suggests that thrust, I_{sp}, and efficiency would continue to increase at greater powers.

5.2. Mass Flow Rate Dependence

The impact of mass flow rate on the thrust, I_{sp}, anode thrust efficiency and discharge voltage is shown in figure 9. Here power was kept constant at 600 W and 0.5 A of current was passed through the magnet coil. All data were taken with a channel depth of 45 mm.

We can observe from figure 9 that increasing mass flow rate results in a slight increase in thrust but a decrease in I_{sp}. The anode thrust efficiency was also found to decrease with increasing mass flow rate, most substantially in the case of the 0 ring magnetic configuration using boron nitride walls. We again see a dramatic performance increase when we change channel material to boron nitride, which we attribute in part to a lower discharge voltage at this power setting. This dictates that both I_{sp} and anode thrust efficiency fall off sharply as mass flow rate is increased for the boron nitride channel with 0 rings.

Figure 9 also shows that increasing the magnetic thickness results in a lower thrust, I_{sp} and efficiency, due in part due to the lower discharge voltage at this power setting. The trends of the 10 rings raised configuration of figure 9 show greater I_{sp} at lower mass flow rates, but a thrust efficiency which is consistent over the range surveyed.

5.3. Magnetic Depth Dependence

The three plots in figure 10 show how thrust, I_{sp}, efficiency and discharge voltage depend on the peak magnetic field strength. The magnetic field strength along the channel centre line at different electromagnet currents was characterised using a magnetic probe before the facility was evacuated, allowing us to deduce the field strength during testing. For these thrust measurements the mass flow rate was fixed at 1.45 mgs^{-1}, the discharge power at 750 W, and the thruster channel was 45 mm deep. We observe a maximum thrust, I_{sp} and efficiency at around 400 G for all trends, with the exception of the 0 rings boron nitride configuration where this maximum is less pronounced yet at a considerably higher field strength of 600 G. At magnetic field strengths above this, we see the performance of the thruster decrease, even though the discharge voltage continues to increase. A performance maximum at a given magnetic field strength has been observed previously in the WET-HET and is assumed to be evidence of the plasma becoming fully magnetised, influencing the motion of both ions and electrons [30, 32]: given

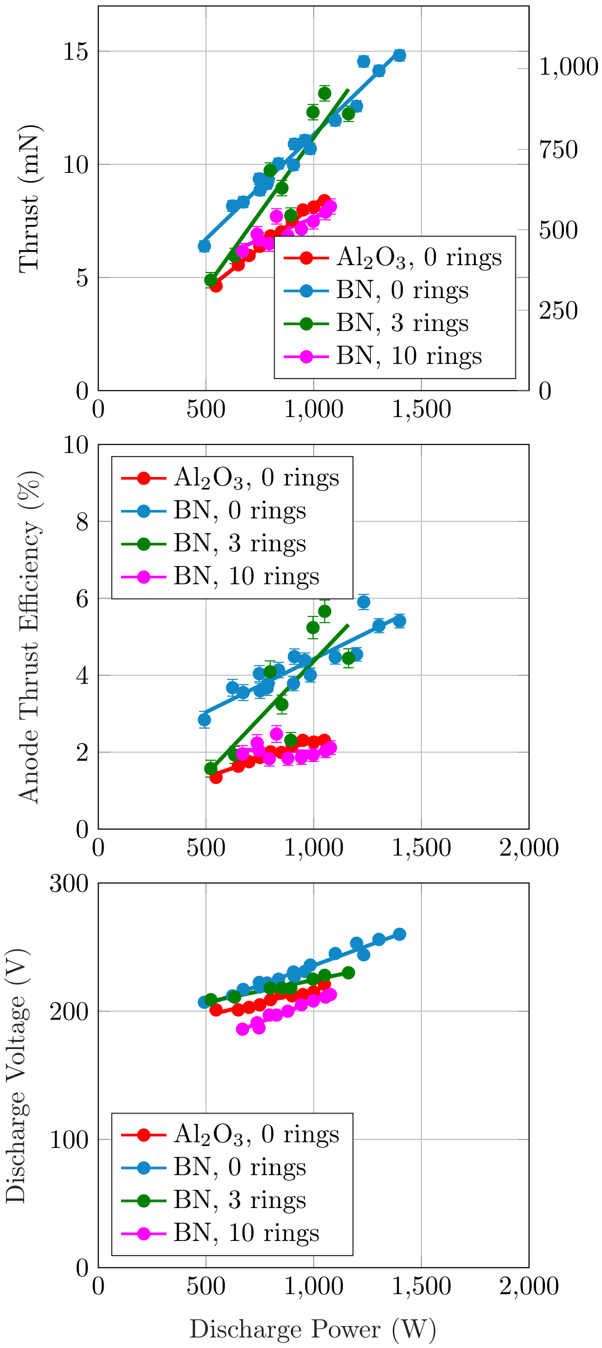

Figure 8: Thrust, specific impulse and anode thrust efficiency as a function of power for the WET-HET with alumina discharge channel (Al_2O_3) and boron nitride (BN). All data were taken with a mass flow rate of 0.958 mgs^{-1}, a magnet current of 1.5 A and a channel depth of 45 mm .

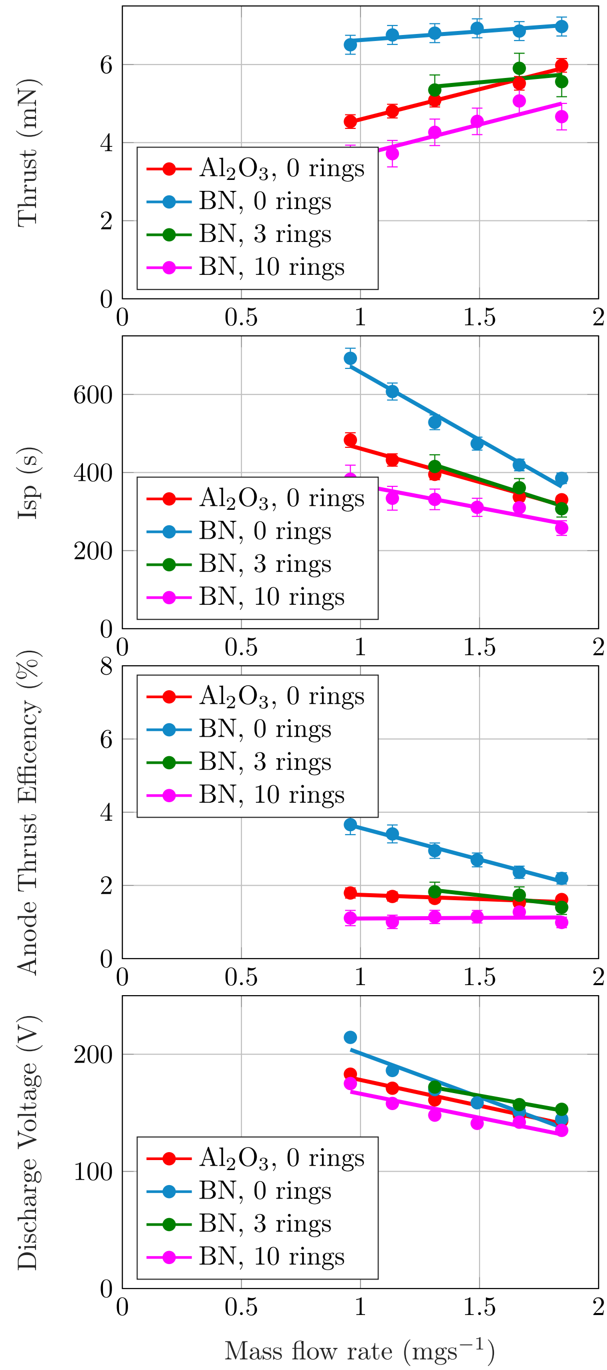

Figure 9: The impact of mass flow rate on thrust, I_{sp} and efficiency for the WET-HET with two different channel materials. All data are at 600 W discharge power, 0.5 A magnet current, and 45 mm deep channel.

the oxygen ions have the same charge but approximately a quarter of the the mass of a xenon ion, they orbit magnetic field lines at only a quarter of the Larmor radius. The magnetic field strength above the performance peaks is assumed to be strong enough to deflect the oxygen ions as they exit the thruster to such a level that performance suffers. This would also explain why the performance maximum of the 0 rings raised BN trend is at a greater magnetic field strength than other configurations: here the magnetic field is only present directly upstream of the channel exit. Even heavily deflected ions are able to exit the channel. Thicker magnetic regions would cause such a deflection further upstream, sending the ion to collide with the wall. This however fails to explain why the 0 rings raised Al_2O_3 trend peaks at the same lower field strength as the thicker magnetic region trends.

A comparable xenon thruster would most probably not

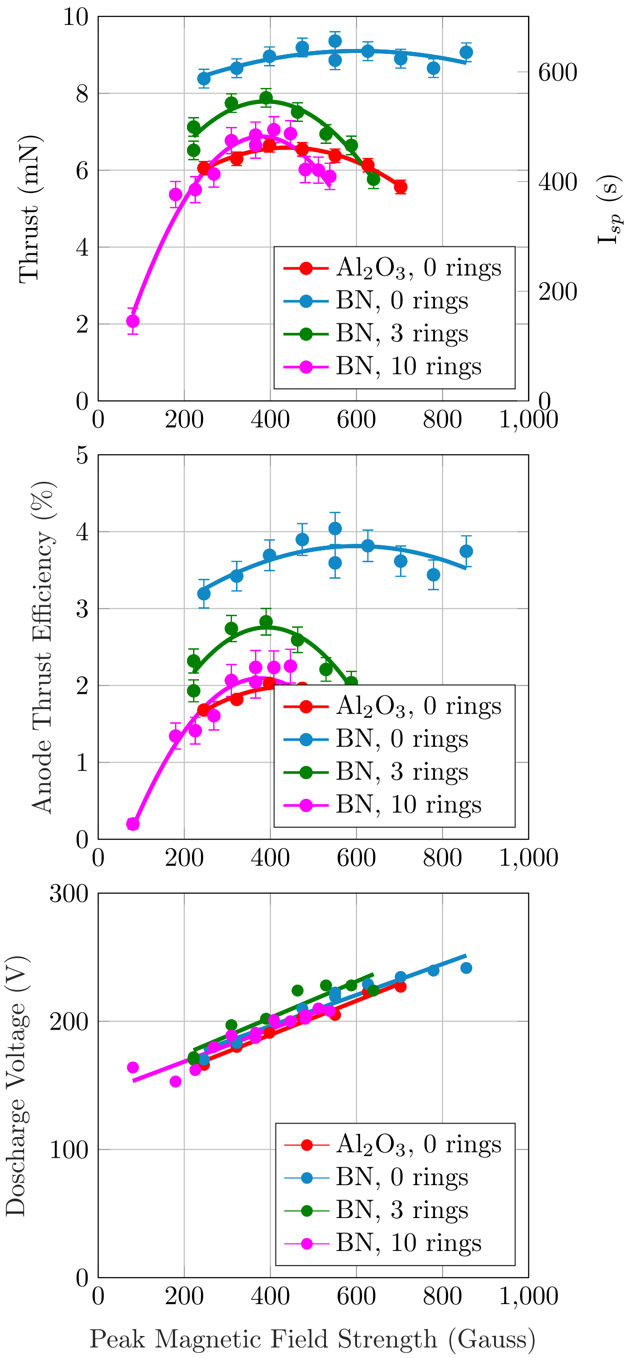

Figure 10: WET-HET thrust, I_{sp}, thrust efficiency and discharge voltage at different magnet currents for three different magnetic depths. All data are at 750 W discharge power, 1.45 mg^{-1} mass flow rate and channel depth of 45 mm.

witness such a decrease in performance until much greater magnetic field strengths. This is due to the heavier xenon atoms having roughly a quarter the charge-to-mass ratio of oxygen and thus four times the Larmor radius, resulting in less deflection. The possibility of fully magnetising the oxygen plasma was considered when designing the WET-HET. This was one of the motivations for a design which allows us to reconfigure the magnetic topology as described above. By decreasing the magnetic field strength, but increasing the thickness of the magnetic region, we hoped to sustain high levels of ionisation without fully magnetising the plasma. Contrary to expectation, figure 10 shows that discharge voltage is unaffected but performance decreases when the magnetic region is broadened. The highest performance achieved was in the 0 rings position, which is that which produces the thinnest magnetic region, and is therefore the most similar to a traditional HET design.

The magnetic depth of the thruster was increased with the intention of broadening the ionisation region of the thruster. We had hypothesised that a broader ionisation region would lead to increased plasma resistance, increased ohmic heating, and therefore a larger voltage drop between the anode and cathode. However, the bottom-most plot in figure 10 shows that all configurations have a very similar discharge voltage at a given magnetic field strength, regardless of magnetic topology or discharge chamber material. This important and surprising result shows that the discharge voltage of the thruster is dependent primarily on the magnetic field strength but not the thickness of the magnetic field profile. By extension this also shows that the discrepancy in thrust, I_{sp}, and efficiency between the different magnetic configuration shown in figure 10 cannot simply be due to a difference in the discharge voltage.

5.4. Channel Depth Dependence

By operating the WET-HET with anodes of different axial lengths, we measure the impact of changing the channel depth of the thruster. This change was made while mass flow rate, magnetic field strength and magnetic topology constant for a range of powers. Figure 11 shows the thrust, I_{sp} and anode thrust efficiency of the WET-HET with channel depths of 35 mm, 45 mm and 60 mm. Data were collected for a range of powers with a mass flow rate of 0.958 mgs^{-1}, a magnetic topology of 0 rings raised, and 1.5 A of current passing through the electromagnets. Boron nitride channel walls were used for all data. We see that changing the channel depth has a surprisingly small effect on thrust, I_{sp} and efficiency. The best performance by a small margin is achieved with the shallowest channel, with the deepest channel having the poorest performance. At powers below 1500 W we see the discharge voltage is independent of channel depth. This changes at higher powers, with the 35 mm deep channel appearing to reach a maximum voltage near 340 V, although efficiency and I_{sp} continue to increase at a seemingly consistent rate.

The 35 mm deep channel with the 0 rings magnetic topology and BN channel walls was shown to be the highest performing configuration of any tested. Not shown in figure 11 are three very high power measurements of the 35 mm trend of the WET-HET operating at 10 A discharge current up to a maximum thrust of 38.63±0.25 mN and an I_{sp} of 4112±36 s. Our confidence in these values is high, yet we were forced to omit these data due to an issue with the data acquisition system which made discharge voltage measurements unreliable,

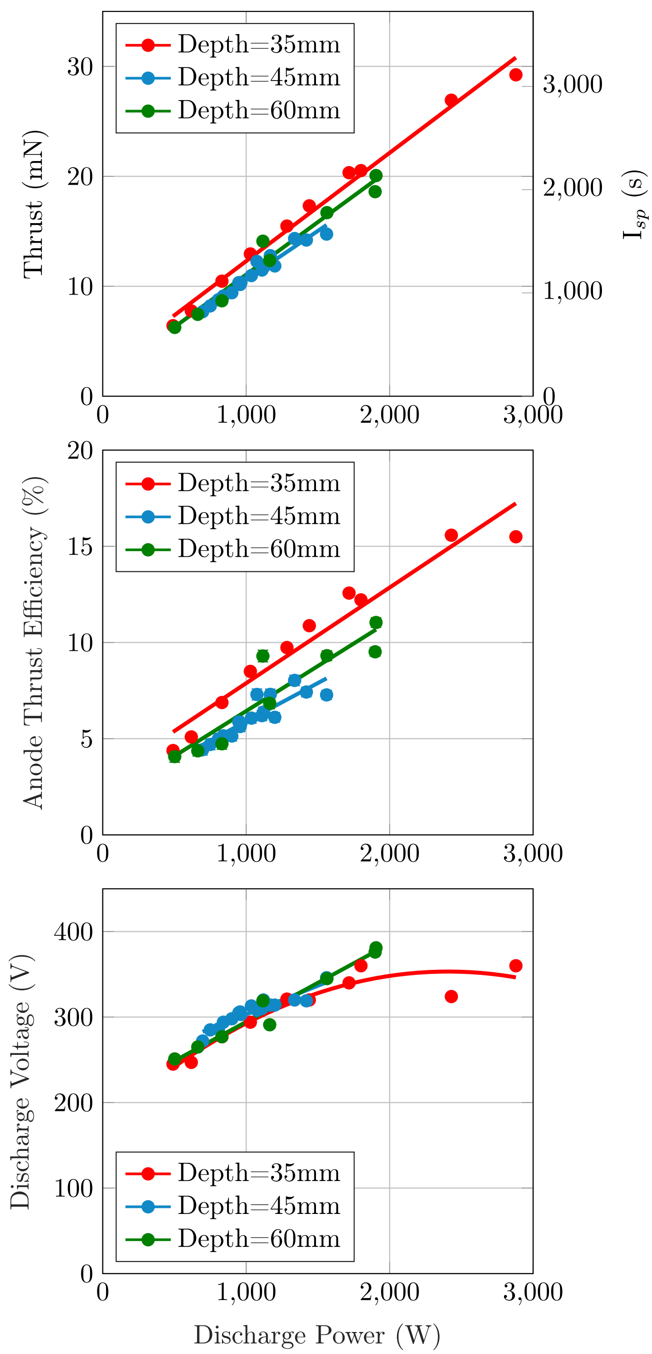

Figure 11: WET-HET thrust, I_{sp}, thrust efficiency and discharge voltage at different channel depths. For all trends the channel wall material is boron nitride, the mass flow rate is 0.958 mgs^{-1} and 1.5 A of current is passed through the electromagnets with a magnetic topology of 0 rings.

meaning discharge power and thrust efficiencies could not be determined with confidence. We estimate that the thruster was operating near 3600 W from which an anode thrust efficiency of 21% can be extrapolated.

6. Discussion and Future Work

Our motivation for changing the channel material from alumina to boron nitride was due to a concern that the alumina material becomes electrically conductive at elevated temperatures, and may be providing a conductive path for the electrons circumventing the plasma. This change has resulted in a significant jump in the thrust of approximately 40%. Alumina has a greater secondary electron emission (SEE) than boron nitride [14]. The secondary electrons emitted from the channel wall have a much lower temperature than those found in the bulk, meaning that an increase in SEE results in a cooler plasma bulk [39]. Both numerical and experimental studies of xenon HETs have shown that channel walls of greater SEE lead to an increase in discharge current and thus a decrease in efficiency at a given discharge voltage [3]. We see the same phenomenon in figure 8, where at a given discharge power the greater SEE of alumina leads to a lower discharge voltage. A lower discharge voltage provides less acceleration potential for the the ions, which ultimately leads to a lower performance at a given power.

One of the considerations when designing the WET-HET for oxygen operation was that magnetic fields of the same strength as in a conventional HET would risk magnetising the ions, given the high charge-to-mass ratio of oxygen ions compared to xenon. We sought to combat this with a thicker, lower strength magnetic field. However, our results have clearly shown that increasing the thickness of the magnetised region is detrimental to thrust, I_{sp} and efficiency at all points tested. Oxygen and xenon differ greatly in terms of mass and ionisation cross section, yet we have shown that like xenon, oxygen benefits from a thin magnetic region near the exit of the thruster. This observation is corroborated in literature: the effect of thickening the magnetic region in a typical xenon hall effect thruster to determine changes in the plasma profile was numerically performed by Ahedo and Escobar [1] using a one dimensional macroscopic plasma model. They found that as the magnetic field is broadened, the region of ion back-streaming near the anode was reduced in axial length, which pulled both the ionisation region and the acceleration region further upstream. As the acceleration region becomes axially longer, wall energy losses increase, which ultimately results in a decrease in thrust efficiency [1]. The same efficiency trends are observed for the WET-HET, for example in figure 10 where we clearly see a decrease in anode thrust efficiency as we increase the axial thickness of the magnetic field. Plasma diagnostic data of the WET-HET are required before we can confirm whether a similar shift in the plasma profile is responsible for the trends we have observed.

In the same study Ahedo and Escobar [1] investigated the thruster response to change in the channel depth at a given discharge voltage. They found that increasing channel length has little effect on the location of the beginning of the acceleration region, but that this region grows in axial length with the channel depth. A thicker acceleration region then contributes to a greater wall loss. They conclude that a shorter channel generally produces a greater efficiency, up to a critical point below which the electron temperature and performance rapidly drop [1]. We appear to see the WET-HET efficiency follow a similar trend, in that the shortest channel tested was the highest performing, suggesting the critical channel depth is less than 35 mm. However, the 60 mm long channel outperformed the 45 mm channel by a small margin which is unexpected. It was originally hypothesised that a very deep channel may be contributing to a greater rate of oxygen dissociation which would increase the ratio of atomic ions to molecular ions. One theory is that such an increase in performance due to the greater average charge-to-mass ratio outweighs the channel wall power losses for deep channels. Such a performance increase at deeper channels would be a direct consequence of the molecular nature of oxygen, which would explain the discrepancy between our results and numerical xenon simulations in the literature. Future plume measurements are planned to determine the charge-to-mass ratio of ejected ions to determine whether this is factor in the performance shift.

Let us compare the propellant utilisation efficiency α of the WET-HET to that of a traditional xenon HET. This is generally defined as the fraction of neutral particles which converted into ions by the device:

$$\alpha = \frac{I_i}{I_{\dot{m}}} \tag{2}$$

Where I_i is the ion current and $I_{\dot{m}} = e\dot{m}/m_n$ is equivalent current for the injected mass flow for the elementary charge e and neutral mass m_n [11]. Note that this only holds for singularly charged ions. An important feature of molecular propellants is that a single neutral particle could potentially dissociate, with all daughter particles becoming ionised, setting the maximum propellant utilisation efficiency for oxygen at 2. If we again assume all ions are singularly charged, we can calculate this efficiency by expressing thrust as a function of ion mass flow times the ion velocity in the form:

$$T = \alpha\dot{m}\sqrt{U_d(1-\delta)2e/m_n} \tag{3}$$

For discharge voltage U_d and the discharge voltage loss coefficient δ [11, 5]. This coefficient is related to the discharge efficiency, such that $U_d(1-\delta)$ is the actual potential the ions really experience [8]. We do not know the value of the discharge voltage loss coefficient for the WET-HET, yet for xenon thrusters it is generally estimated to be between δ<0.1 and δ=0.3 [18]. To be conservative we shall assume delta is in the range of 0>δ>0.5. From the propellant utilisation efficiency we can now calculate the mean ionisation length λ_i, which is the average distance that a neutral particle will travel before becoming ionised. We can calculate the mean ionisation length from the propellant utilisation fraction by comparing it to the channel depth L [11]:

$$\lambda_i = \frac{-L}{\log(1-\alpha)} \tag{4}$$

We can calculate the propellant utilisation efficiency of the WET-HET from equation 3 for the thrust and discharge voltage shown for the L=35 mm trend in figure 11. We plot this, along with the mean ionisation length given by equation 4 in figure 12. We assume the real value will fall somewhere within the δ=0 and δ=0.5 trends. For comparison, we also include data for an SPT-100 thruster with δ=0.05 operating on xenon. For this we use experimental data from Sankovic and Hamley 1993, at a discharge voltage of 300 V and mass flow rates ranging from 3.45 mgs^{-1} to 5.45 mgs^{-1} [28]. We can see that the WET-HET requires considerably higher discharge powers to achieve propellant utilisation efficiencies and mean ionisation lengths comparable to a traditional xenon thruster. An alternative way to define the ionisation length is by the approximation [8]:

$$\lambda_i \approx \frac{v_n}{n_n\sigma_i(T_e)v_e(T_e)} \tag{5}$$

Where v_n and v_e are the velocities of the neutrals and electrons respectively, n_n is the neutral density, and σ_i is the ionisation cross section as a function of electron temperature T_e. The WET-HET and SPT-100 operate at similar volumetric flow rates of 40-60 sccm, yet the WET-HET has a smaller channel cross section by a factor of 13.3. Consequentially the neutral density of the WET-HET is considerably higher. Equation 5 shows us that the results in figure 12 indicate the WET-HET is only able to produce a similar mean ionisation length (and by extension propellant utilisation efficiency) by combating the low ionisation cross section of oxygen with a high neutral density. Even then the ionisation length is only similar when the WET-HET is operating at very high powers, which presumably generates a high electron temperatures. We note that the utilisation efficiency and ionisation length appear to plateau above 2 kW, which is a result of the voltage plateau seen in the same data in figure 11.

Many xenon HETs are designed by modifying successful thrusters using scaling laws, derived using fundamental plasma theory. However, given the large differences expected between a xenon and oxygen plasma and the lack of available data on prior oxygen HETs, our approach was to optimise the thruster using a zero-dimensional particle-in-cell model to capture the influence of geometric and field parameters self-consistently [33]. One of the results of this optimisation was a considerably smaller channel cross section of a thruster in this power class, but also a greater surface-to-volume ratio. The WET-HET has approximately 2.5 times the area per unit volume as a conventional SPT-100. The increase of the surface-to-volume ratio was a direct consequence of reducing the channel cross section to increase neutral density at the target mass flow rate. The experimental findings illustrate the efficacy of this approach. The thruster was able to maintain a stable discharge at the low propellant flow rate of 0.985 mgs^{-1}, at discharge powers in excess of 3 kW. Under these conditions we observe a high propellant utilisation efficiency as seen in figure 12. Increasing the channel cross section area would require a greater mass flow rate to achieve the same density, and thereby even higher discharge powers to attain the same propellant utilisation efficiency. There is, however, an important trade-off to consider. A consequence of a high surface-to-volume ratio is increased

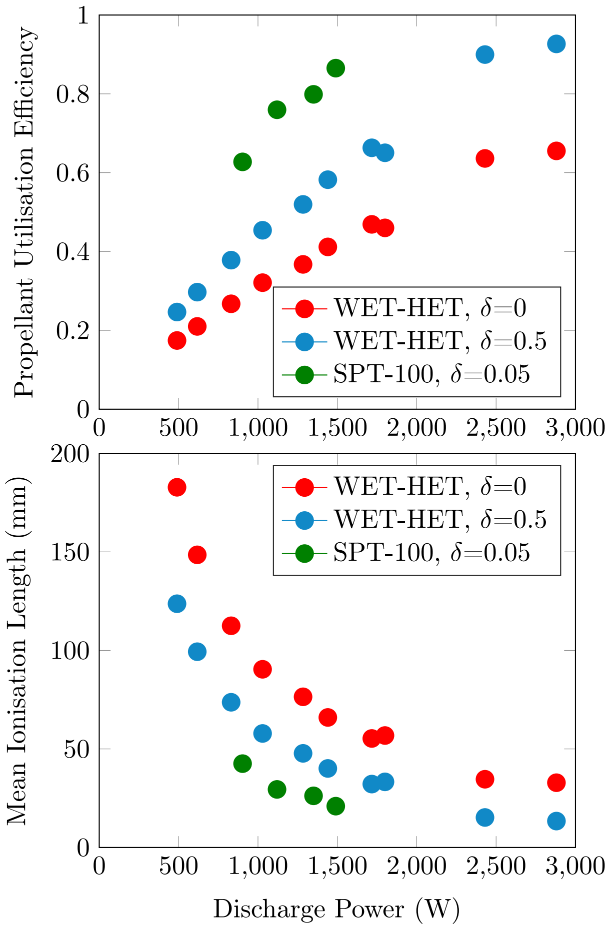

Figure 12: Propellant utilisation fraction and mean ionisation length of the WET-HET and an SPT-100 operating on xenon as a function of discharge power. The WET-HET data were taken at the same conditions as those in figure 11. SPT-100 data is taken from using experimental data from Sankovic and Hamley 1993 [28].

power losses to the wall, and thereby a further reduction of thrust efficiency. During testing we witness high thermal loads on the channel walls, driven by these wall losses, evidenced by visibly glowing of the ceramic walls at high discharge powers

Previous simulations have suggested that the ratio of diatomic ions (O_2^+) to monatomic ions (O^+) is a function of the residence time of the particles, and could therefore be altered by tuning of the channel depth [31]. Future plume measurements of the WET-HET will determine whether the ion ratios are dependent on channel depth, and if this one of the factors leading to the discrepancy in performance.

The ECHT of Marchioni and Cappelli [24] and the WET-HET have similar approaches in optimising a HET for molecular propellant utilisation. The ECHT was here operated on nitrogen, yet similarities of atomic mass, diatomic nature, and ionisation cross section of nitrogen and oxygen allow us to draw comparisons between the thrusters. The ECHT has a deeper channel of 86 mm, double the channel width, and four times the outer diameter. The ECHT has almost 9 times the cross sectional area of the WET-HET, yet operates at higher anode thrust efficiencies at only twice the mass flow rate at comparable discharge powers of 520 W to 770 W. The two thrusters differ in that the ECHT operates at greater anode thrust efficiencies as discharge power is reduced, where the opposite is true for the WET-HET. Marchioni and Cappelli [24] plan on conducting more tests with the ECHT after increasing the depth of the ionisation channel, the thickness of the magnetic region, and the radial magnetic field strengths above their current maximum near 100 Gauss. They recognise that after a particular channel length, power losses to the walls will hurt performance, this was also true for the WET-HET for intermediate lengths, but at deep channels the performance began to increase again. For the WET-HET increasing the magnetic region decreased performance, yet this may not be the case for a thruster with such a different channel cross sectional area. The authors agree with Marchioni and Cappelli [24] that the high energy densities required for high performance with molecular propellants will require considerable engineering challenges.

The ultimate goal of the WET-HET is to test the feasibility of operating a HET on water electrolysis, meaning the anode operates on oxygen, with the stoichiometric ratio of hydrogen supplying the cathode. Future experiments will test such a configuration with a LaB_6 cathode more representative of flight hardware operating on hydrogen propellant.

The WET-HET is a proof of concept thruster which serves as a test bed for testing different configurations and test conditions for oxygen operation. The results of this test campaign provide clear suggestions for how further alterations could be made to an oxygen thruster to increase performance. Our experimental findings suggests that the magnetic region should be as thin as possible. It was found that the optimal magnetic field strength was approximately 480 Gauss for this channel geometry and magnetic field shape. We also suggest that the thruster should be operated at the lowest mass flow rate required to sustain the discharge in order to maximise the propellant utilisation efficiency. The thruster efficiency was found to improve with increasing discharge power up to the maximum power surveyed in this study.

7. Conclusion

We have investigated the feasibility of a HET using in-situ water electrolysis by experimentally measuring the performance of a laboratory prototype that was designed to operate on oxygen as a propellant.

The thruter was operated on powers ranging from 492 W to 2880 W, and mass flow rates of oxygen ranging from 0.985 mg^{-1} to 1.85 mg^{-1}. The maximum thrust recorded was 38.63±0.25 mN which results in a maximum I_{sp} of 4112±36 s. The greatest anode thrust efficiency we measured was 15.50±0.27%.

The best performance is generally found at greater discharge powers, low mass flow rates, and radial magnetic field strengths near 400 Gauss.

We find that changing the channel walls from alumina to boron nitride increases thrust by almost 40%, which we attribute to the lower SEE.

The influence of the magnetic field thickness on the thruster performance was investigated using three magnetic topologies. It was found that the highest performance was attained using the thinnest magnetised region, and lowest performance for the thickest magnetised region.

We find that the best performance was found by reducing the channel depth to its minimum, yet a deep channel also outperformed a channel of intermediate depth.

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