Sizing and Preliminary Design of a 2-kW Water Propelled Hall Effect Thruster

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IEPC-2022-317

Presented at the 37th International Electric Propulsion Conference
Massachusetts Institute of Technology, Cambridge, MA USA
June 19-23, 2022

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Having identified the potential of water as a breakthrough propellant for electric propulsion, URA Thrusters and Imperial College London present the preliminary design of a 2-kW level water vapor fueled Hall Effect thruster: the AQUAHET. The design of this new thruster builds on the lessons learnt from the development at Imperial of an analogous oxygen fueled thruster: the Water Electrolysis Hall Effect Thruster or WET-HET. Using a 1D version of Imperial College London's fully kinetic particle-in-cell code PlasmaSim, we determine the optimum discharge channel sizing for the AQUAHET. The presence of multiple high specific impulse and anode efficiency data points outputted by these analyses points to sources of unaccounted losses in the code. To verify PlasmaSim's ability to accurately predict thruster performance with water vapor, we conduct an early prototype validation test campaign. For these experiments existing WET-HET laboratory prototype hardware is adapted and tested at a channel length of roughly 13 mm, a channel mean diameter of 20 mm, and a channel width of 5 mm. Thrust data is collected with a hanging pendulum style thrust balance for mass flow rates of 1 mg/s of oxygen and water. For oxygen at discharge powers ranging from 710 to 1580 W we measure thrust up to 22 mN, specific impulse up to 2342 s, and anode efficiency up to 16.5%. For water at discharge power levels ranging from 860 to 1600 W we measure thrust up to 20 mN, specific impulse up to 2039 s, and anode efficiency up to 12.5%. Comparison of this experimental data against PlasmaSim outputs underlines the code is not currently able to accurately predict water performance. We posit this is in part because the model fails to correctly capture collision physics. In order to leave room for future experimental performance optimization, a modular AQUAHET thruster is designed with channel lengths of 7, 10, and 13 mm; a channel mean diameter of 20 mm; and channel widths of 3, 4, and 5 mm. We also present here the updated magnetic topology of the AQUAHET breadboard thruster.

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I. Introduction

Heritage electric propulsion (EP) devices like Hall Effect Thrusters (HETs) have to date relied heavily on xenon as a propellant. The heaviest of the non-radioactive noble gases, xenon is chemically non-reactive and can be stored at relatively low pressures. A large ionization cross section combined with a low first ionization energy leads to a high ionization rate, and thus a high propellant utilization efficiency [1]. The continued use of xenon is however limited by its cost and scarcity. Few industrial applications require the propellant and global production is limited, meaning supply and demand fluctuations result in a very unstable price. For context, a single large NASA mission using EP can require more than 10% of the global annual xenon production [2] and the price of the propellant has increased tenfold in less than eight years [3]. Additionally, even though it is usually regarded as a green propellant, xenon's production process has a large carbon footprint. Separating and purifying a single kilogram of xenon from the atmosphere can indeed require up to forty times the amount of energy needed to produce one kilogram of titanium [4].

As the rise in the use of EP propulsion systems stands to further strain the limited global supply of xenon and therefore exacerbate acquisition difficulties for satellite integrators, research into the use of alternative propellants has become increasingly important. To date, this research has focused on noble gases like krypton and argon [5], on metals like bismuth [6, 7, 8], and on the halogen iodine [9,10]. We have identified water as a promising prospect and will describe here the efforts taken to investigate its suitability as an alternative propellant for HETs. Not only is water inherently attractive by virtue of its ubiquity and low cost, but it also stands to offer a number of attractive system level benefits that include, but are not limited to, storability at low pressures, ease of transport, and reduced launch site activity requirements. In the longer term, water-based EP systems could also make use of in-situ propellant utilization off world, which would not be possible with xenon.

Motivated by water's potential as a cost effective, accessible, and environmentally friendly alternative to xenon, URA Thrusters and Imperial College London (ICL) have embarked on the design of a 2-kW level water fueled Hall effect thruster termed the AQUAHET. Development work for the AQUAHET builds on the design and test of an analogous thruster at Imperial: the Water Electrolysis Hall Effect Thruster (WET-HET). The WET-HET is a thruster designed to operate on the products of water electrolysis, i.e. a thruster that operates with oxygen flow to the anode and hydrogen flow to the cathode [11, 12, 13, 14, 15]. In Section II of this paper we will begin by presenting the lessons learnt from the development of the WET-HET. In Section III we then describe how a 1-D version of Imperial's in-house PIC code, PlasmaSim, was used to determine optimum values for the water fueled AQUAHET discharge channel's width, length, and mean diameter. Section IV details how PlasmaSim's ability to correctly optimize for a thruster operating with water vapor was verified experimentally by adapting existing WET-HET hardware available at Imperial for early validation testing. To finish, we will present in Section V the AQUAHET thruster's magnetic topology design.

II. Lessons Learned from the Design and Test of the Oxygen Fueled WET-HET

The Water Electrolysis Hall Effect Thruster (WET-HET) is a key piece in the hybrid chemical-electric propulsion architecture being developed at URA Thrusters in partnership with Imperial College London. In this hybrid propulsion system, the oxygen and hydrogen produced through the electrolysis of water are used to feed both a chemical and an electric engine. The WET-HET is operated within this architecture with oxygen flow to the anode and hydrogen flow to the cathode [4].

The design of the WET-HET at Imperial College London began with sizing of the thruster's discharge channel. In this initial design phase channel width, length, and mean diameter were optimized for oxygen operation using a simplified version of Imperial's in-house PIC code PlasmaSim. Simplifying assumptions for the quasi-zero-dimensional version of the code used, referred to internally as PlasmaSim-0D, are described in more detail by Schwertheim et al. in [12]. A channel width of 5 mm, lengths of 35-60 mm, and a mean diameter of 20 mm were selected for the WET-HET. In the subsequent detailed mechanical design phase, choices were guided by axisymmetric thermal and magnetostatic simulations performed using Finite Element Method Magnetics (FEMM).

The WET-HET laboratory model thruster built then underwent performance characterization tests at the Imperial Plasma Propulsion Laboratory's (IPPL) Boltzmann vacuum facility. The thruster was operated at oxygen anode mass flow rates between 0.96 and 1.85 mg/s, power levels between 400 and 2880 W, and magnetic circuit currents between 0.5 and 2.5 A [13, 14, 15]. For these tests, a filament plasma bridge neutralizer operating on 15 sccm of krypton was used. Performance measurements were collected with the group's hanging pendulum style thrust balance [16]. IPPL researchers measured thrust up to 38.63 ± 0.25 mN, specific impulse up to 4112 ± 36 s, and anode efficiency up to 15.50 ± 0.27%.

When comparing these initial PlasmaSim-0D predictions to experimentally measured data we found that performance trends as a function of power and mass flow rate were predicted accurately. However, the performance data collected was significantly lower than initial code forecasts. This mismatch was attributed in part to the fact that PlasmaSim-0D did not account for several key energy loss mechanisms. These included non-ionizing dissociation and excitation to rotational-vibrational states [13].

A quasi-1D implementation of PlasmaSim was subsequently developed by the group at Imperial College London [17]. Using the lessons learnt from initial comparisons of the code outputs to experimental measurements, the second largest electron-oxygen collision by cross-section, ionizing dissociation, was implemented. As can be seen in Fig. 1, it was found that this newer 1D version of the code showed a good match with the oxygen experiments, highlighting the importance access to benchmark experimental data can have in guiding improvements to a group's simulation tools.

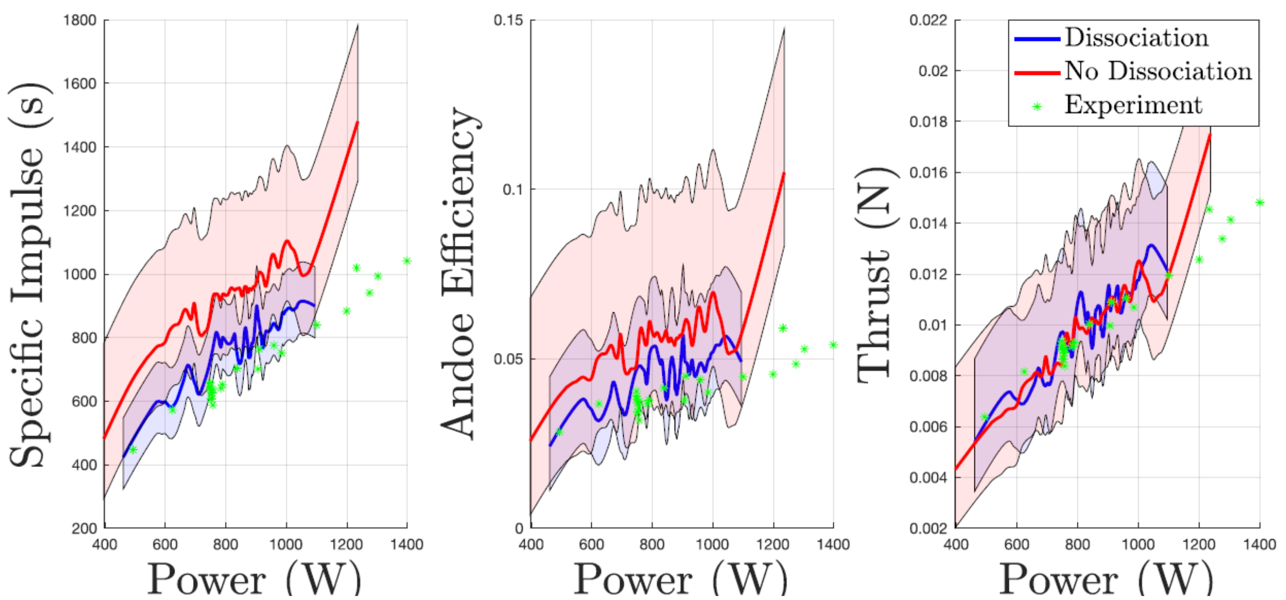
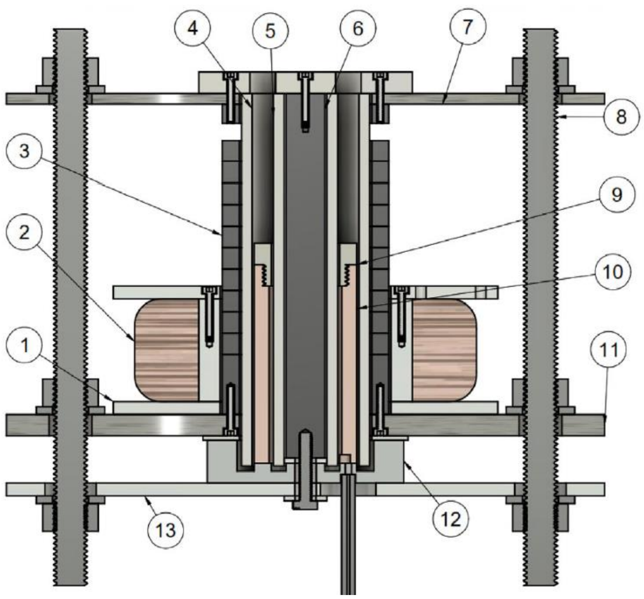


Fig. 1 Specific impulse, anode efficiency, and thrust as a function of power when comparing 1D PlasmaSim with and without dissociation to experimental measurements collected with the oxygen fueled WET-HET [17]

As it was anticipated at the time of design that oxygen's lower ionization cross section would result in fewer neutrals being ionized within the WET-HET's magnetized region, a topology with a radial magnetic field extending further into the channel than is customary for xenon HETs was proposed. Thus, the Hall current depth could be increased, which we had hoped would ultimately increase the likelihood of electron-neutral collisions. As increasing magnetized length can also potentially result in a reduction of the acceleration region, and so in turn result in a reduction of ion velocity, thruster hardware with a modular magnetic topology was built. The WET-HET's outer magnetic pole consists of a stack of iron rings which can be raised or lowered to alter the magnetic thickness in the channel (see Fig. 2). This magnetic design had the marked advantage of allowing us to determine the optimum topology experimentally. Data collected showed the thinnest magnetic field configuration resulted in the highest performance [15]. However, in the thinnest configuration (0-rings raised) field lines close to the channel exit plane are slanted towards the inner ceramic wall. This is visible in Fig. 3. We posit this was in part responsible for the preferential erosion of the inner wall observed during testing. In consequence, efforts were made when designing the AQUAHET thruster's magnetic topology to ensure field lines were as horizontal as possible in the region close to the chamber exit plane.



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	Stainless steel
10	Anode	Copper
11	Back plate	Stainless steel
12	Tail cap	Stainless steel
13	Radiator	Aluminium

Fig. 2 WET-HET cross section and materials description [13]

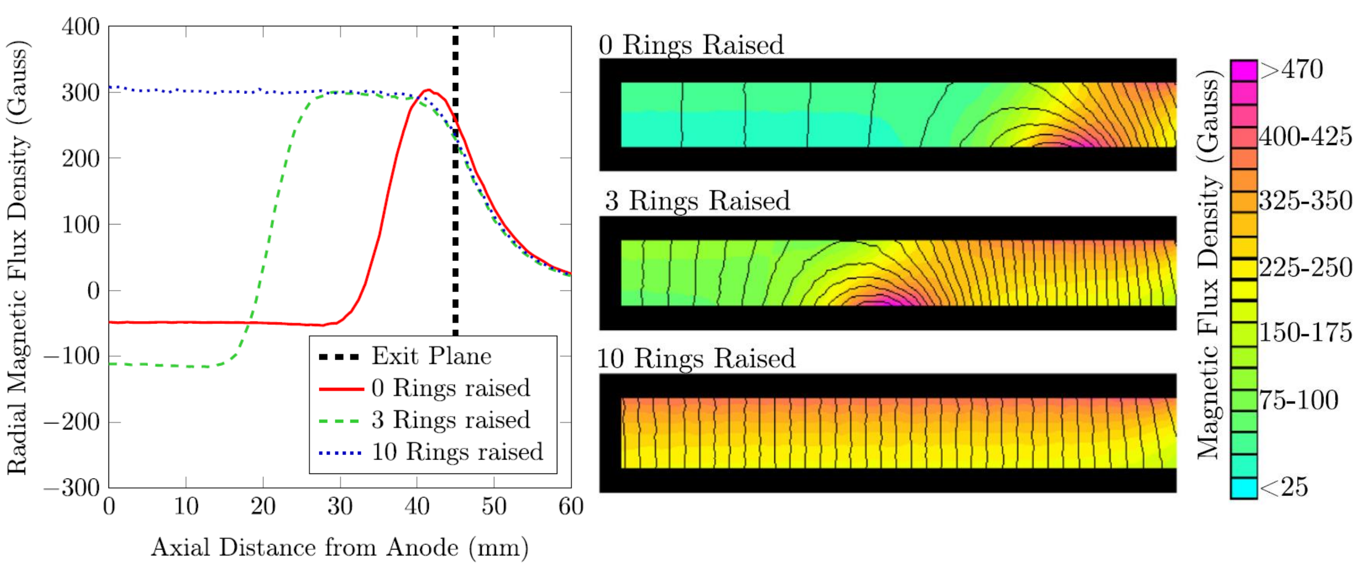


Fig. 3 FEMM simulation of the magnetic flux density for three topologies. Left: radial flux density along the channel centerline. Right: field lines and flux density norm [15]

In Ref. [13] the radial magnetic flux density for the WET-HET's thinnest configuration at magnet currents ranging from 0.5 to 2 A is shown as predicted by the FEMM axisymmetric magnetic model and as measured using a magnetic probe (see Fig. 4). The discrepancy between simulated and measured values is attributed here to the non-axisymmetric nature of the thruster magnetic railing which FEMM cannot capture. The magnetic design approach was therefore adapted for the AQUAHET thruster. In the first instance, an axisymmetric model was set up in FEMM. This was to allow for rapid design iterations. Once an initial topology had been converged on, a 3D magnetostatic model with ¼ symmetry conditions was set up in COMSOL. This ¼ symmetry model was used for final sizing of the coils and final adjustments to the AQUAHET's magnetic railing.

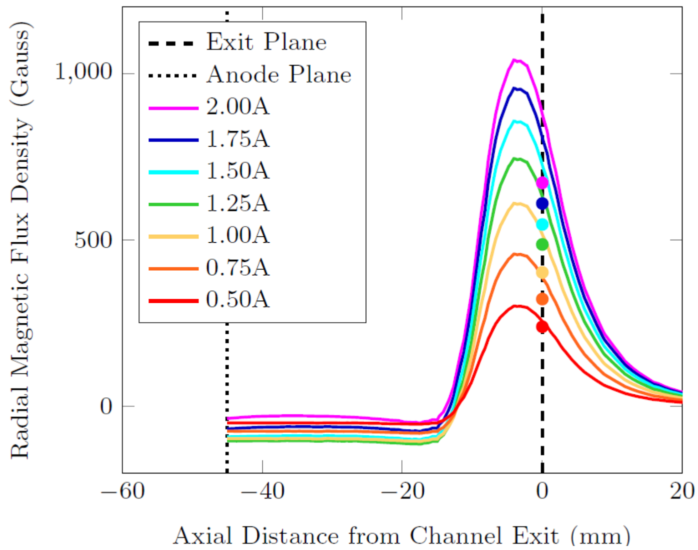


Fig. 4 Radial magnetic flux density along the center of the channel at different currents in the WET-HET's 0-rings raised configuration. Circles show the experimental values [13]

III. Discharge Channel Sizing of the 2-kW Water Fueled AQUAHET

Encouraged by the promising initial WET-HET oxygen experimental performance results presented in the previous section, URA Thrusters and Imperial College London decided to investigate the degree to which a HET can be optimized for operation with direct water vapor feed to the anode. Operating a HET directly with water has the noteworthy advantage of removing the need for an electrolyzer in the thruster's propellant feed architecture. This is especially useful as electrolyzers have been identified as the lowest overall TRL component for hybrid chemical-electric propulsion architectures [18]. To this end, a breadboard model of the water based AQUAHET thruster was developed.

The first step in the conceptual design of the 2 kW AQUAHET thruster breadboard model consisted in determining the three optimal characteristic dimensions of its discharge channel: the channel length [L], mean diameter [D], and width [W]. This was achieved using the 1D version of PlasmaSim that accounts for dissociation (see example outputs for oxygen runs in Fig. 1). Note that the WET-HET oxygen thruster used as a baseline for the AQUAHET design had a channel length of 35-60 mm, a channel mean diameter of 20 mm, and a channel width of 5 mm.

N.B. *In each of the thrust-to-power ratio (TTPR) as a function of specific impulse plots included in this section we draw iso-lines for the anode efficiency η.*

A. PlasmaSim Operating Principles

PlasmaSim is a fully kinetic PIC code developed by Imperial College London that employs a Boris pusher method for time integration and Direct Simulation Monte Carlo (DSMC) for collision modelling. In PIC simulations, each particle is tracked as an individual element in continuous space, while forces and fields are evaluated at discrete locations. The forces acting on the particles are resolved by interpolation. The code's time integration algorithm, the Boris pusher method, was selected for its numerical stability, with details of its implementation to be found in [19]. A statistical method that relies on relative particle velocities, DSMC is used for both neutral-neutral and neutral-electron collisions. PlasmaSim's computation domain differs somewhat from more commonly used PIC approaches as it consists of an 'unrolled' channel, as can be seen from Fig. 5.

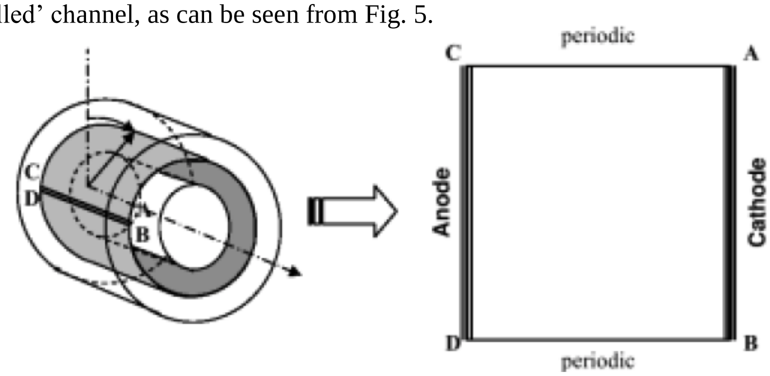


Fig. 5 Illustration of PlasmaSim's computational domain [17]

Details of the most recent improvements made by the group to a pseudo-2D version of PlasmaSim can be found in references [20, 21]. Note however that the results presented within this paper were obtained using a 1D version of the code. Further information on the 1D version of PlasmaSim used here is provided by Jones-Tett in ref. [17].

B. Channel Length Sizing Results

Initially, thruster performance was investigated for channel lengths between 13 and 21 mm (see Fig. 6). It was found that thruster performance increased with a decrease in length, which prompted a further investigation of performance for channel lengths between 13 and 7 mm (see Fig. 7). Note that in both of these cases the width and mean diameter varied between 3-5 mm and 15-25 mm respectively.

The performance trend between channel lengths of 7 and 13 mm became less clear, with high specific impulse data points that suggest the presence of unaccounted losses and potential errors in PlasmaSim appearing for the 7 mm length runs. Given that PlasmaSim water simulations had yet to be validated experimentally at the time of this conceptual design, it was decided to build a thruster model with modulable channel lengths that ranged between 7 and 13 mm. More specifically, it was decided that a thruster model with lengths of 7, 10, and 13 mm would be built.

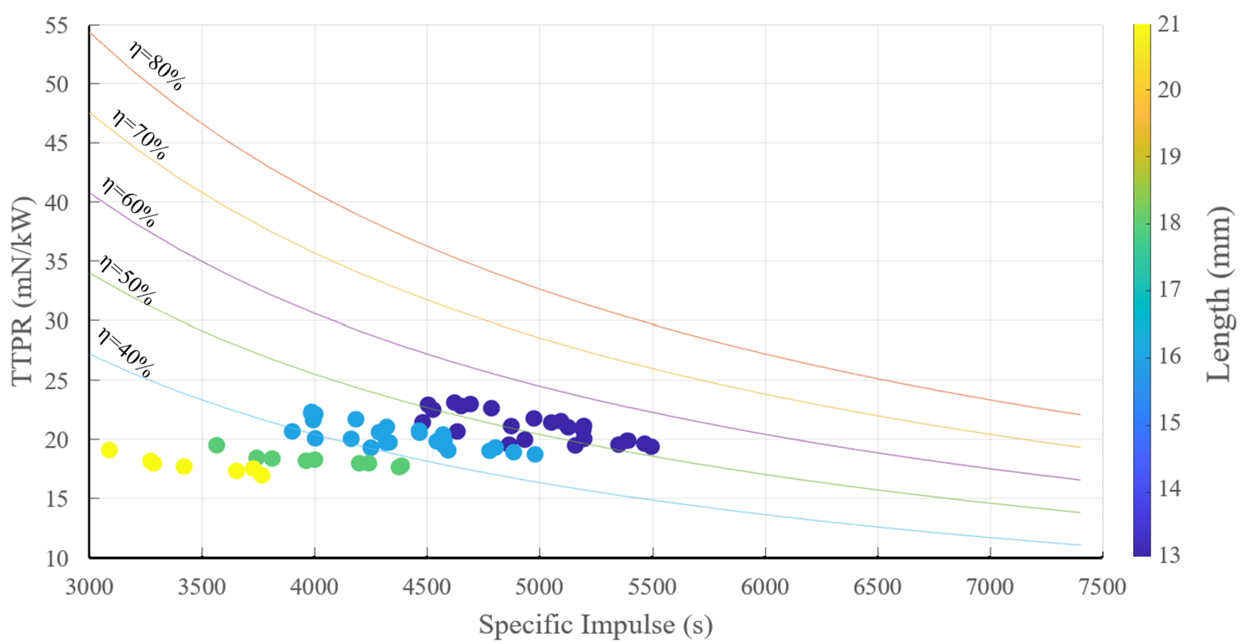


Fig. 6 TTPR as a function of specific impulse for water fueled AQUAHET channel lengths between 13 and 21 mm

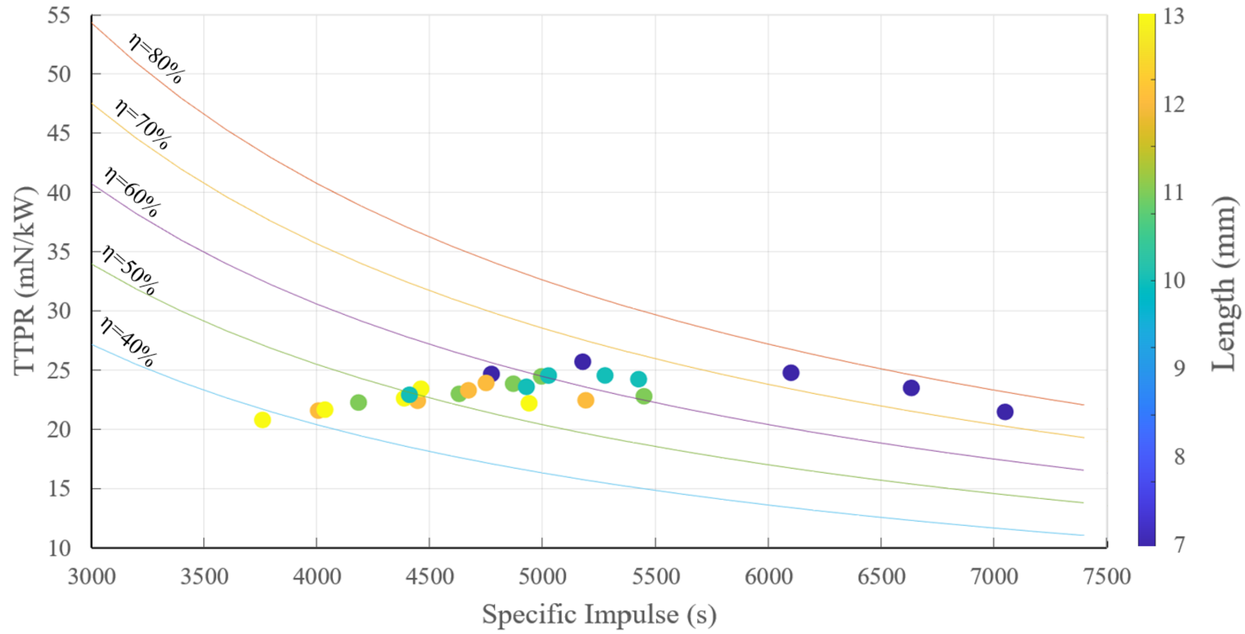


Fig. 7 TTPR as a function of specific impulse for water fueled AQUAHET channel lengths between 7 and 13 mm

C. Channel Mean Diameter Sizing Results

It can be seen from Fig. 8 that there is no clear performance trend when the diameter of the discharge channel is varied between 15 and 25 mm. Note that here we have W ∈ [2.5; 3.5] and L=13. In the interest of simplicity, a mean diameter of 20 mm, matching that of the WET-HET oxygen thruster, is selected.

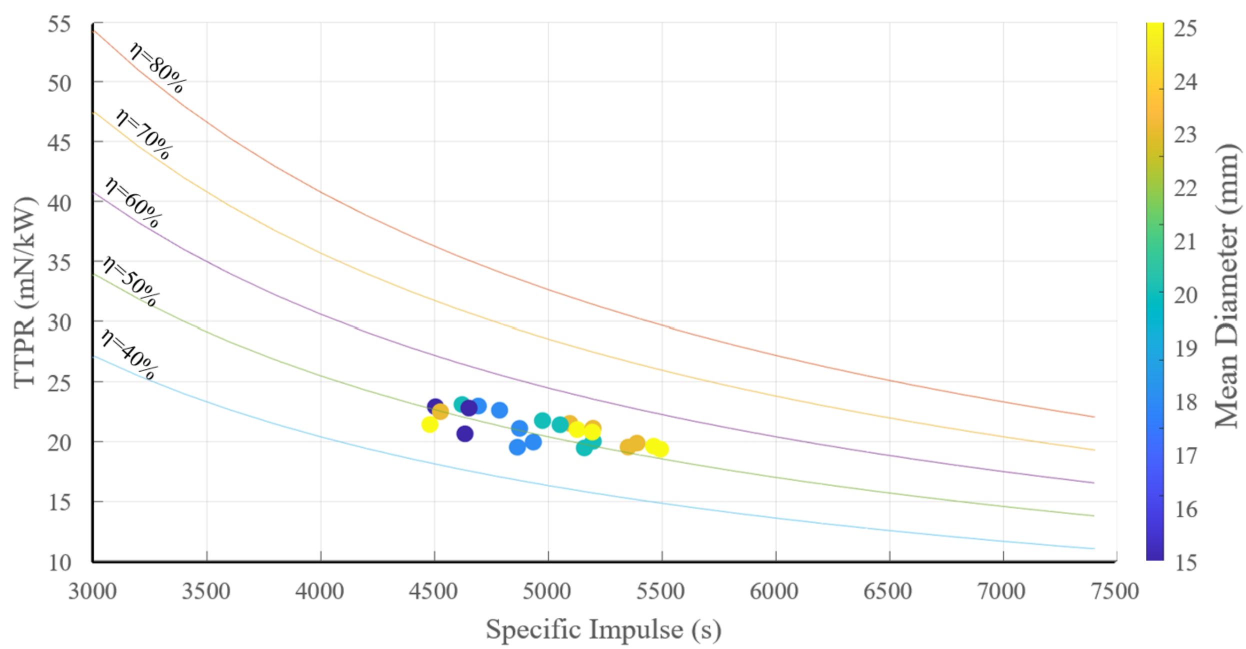


Fig. 8 TTPR as a function of specific impulse for water fueled AQUAHET channel mean diameters between 15 and 25 mm

D. Channel Width Sizing Results

Thruster performance was investigated for channel widths ranging from 3 to 5 mm, while D ∈ [15; 25] and L = 13. Setting aside a small subset of points in the 6000-7500 s specific impulse range that seemed to point again towards a source of unaccounted losses in PlasmaSim, Fig. 9 showed that at a certain width threshold value both the specific impulse and TTPR decreased, indicating a negative performance impact in the case of a continued increase of the width. Based on these simulations, and on the presence once again of outlier performance points, it was decided to build a thruster with modulable channel width. This was considered especially important as the width is known to have a strong impact on HET performance. While it would have seemed from the simulations that widths between 3 and 4 mm would perform best, a decision was made to build a water HET with channel widths of 3, 4, and 5 mm. Indeed, concerns that the iteration of PlasmaSim used for these 2-kW water HET sizing runs might be insufficiently accounting for wall losses led us to favor widths which would minimize the surface to volume ratio.

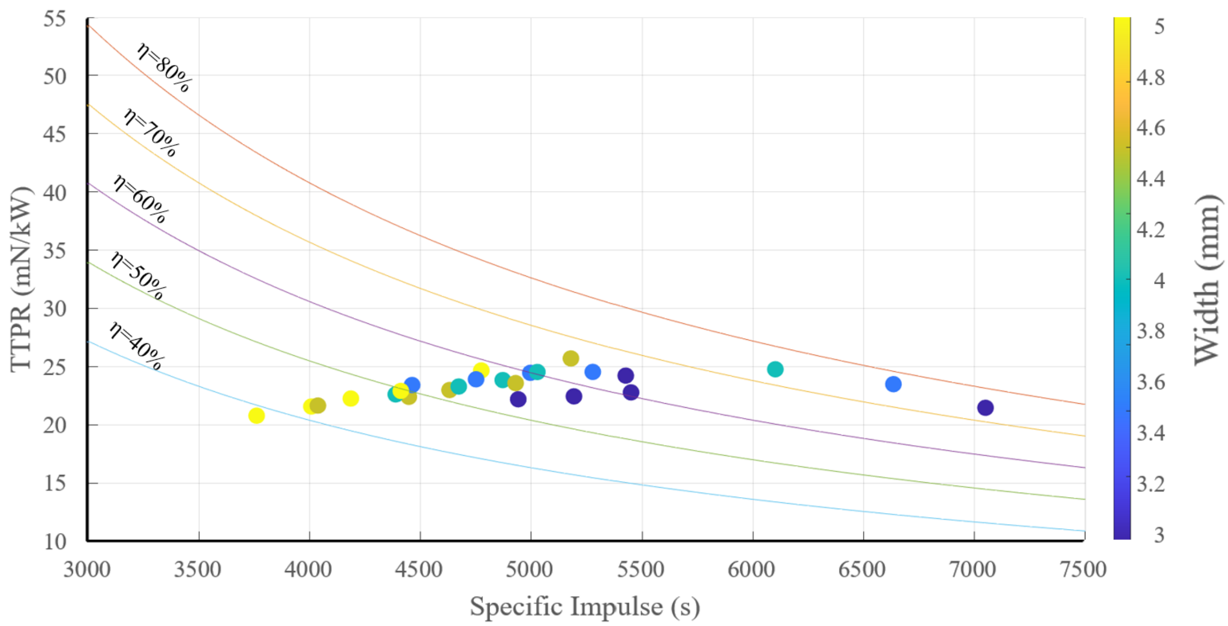


Fig. 9 TTPR as a function of specific impulse for water fueled AQUAHET channel widths between 3 and 5 mm

IV. Early Prototype Simulation Validation Testing

Testing of the WET-HET oxygen-based thruster highlighted how important access to benchmark experimental data is in guiding improvements to simulation tools. As it became quite clear from the results of the AQUAHET discharge channel sizing simulations that the 1D version of PlasmaSim used here contained sources of unaccounted loss we considered the collection of benchmark experimental water data to be all the more important. As such, a decision was made to conduct an early prototype simulation validation test campaign. In this campaign, existing WET-HET laboratory model prototype thruster hardware available at the IPPL was adapted to match discharge channel sizing outputs from the PlasmaSim water optimization runs. Namely, an adapted WET-HET thruster with a channel length of 13 mm, a channel mean diameter of 20 mm, and a channel width of 5 mm was manufactured and tested with both oxygen and water.

A. Experimental Setup

The experimental campaign was conducted at the Boltzmann vacuum facility within the IPPL [22]. The testing facilities are composed of two adjacent vacuum chambers arranged in a T-shape ("main" and "load-lock hatch" chambers), with approximate dimensions of 1.5 x 2 m (diameter x length) and 0.75 x 1.5 m (diameter x length) respectively. Three vacuum stages allow testing under pressure conditions of approximately 10^{-5} mbar, pressure conditions which were maintained during the whole campaign. These three stages are:

- First stage: roughing pump, which enables vacuum levels down to ≈10-2 mbar.
- Second stage: two Leybold turbomolecular pumps, with a pumping speed of 2200 L/s xenon. These pumps lower the chamber pressure down to ≈10-5 mbar.
- Third stage: Leybold cryopanel, with a pumping speed of 15,000 L/s xenon. This pump does not decrease the vacuum level but helps keep the vacuum level conditions constant to ≈10-5 mbar when there is mass flow coming to the chamber. This is accomplished by freezing the molecules which contact the panel.

For the thrust measurements, a hanging pendulum thrust balance was used [16]. The precision of the balance permits testing of electric propulsion devices with a thrust precision level lower than 1 mN.

Regarding oxygen and water testing, two different feedlines were used for each propellant. In the case of oxygen, a mass flow controller and a series of strategically located valves were used to feed propellant into the thruster. In the case of water however, a more sophisticated system was needed to prevent water condensation throughout the line. Several iteration processes concluded that the shorter the overall feedline length and the thicker the tubing used, the lower the pressure/pressure losses are throughout the line. It was found that lowering the overall pressure in the line and minimizing pressure loss was effective at mitigating water condensation. To enable stable, long duration testing, a heater was also needed to elevate the temperature of the line. A pressure transducer was used to monitor the pressure at all times and a transparent section of the line allowed for visual inspection to crosscheck if water condensation was occurring. With this set-up, the thruster could operate nominally at mass flow rates of up to 2 mg/s of water vapor. Note that with the existing setup we see condensation in the line for long duration tests at mass flows above 2 mg/s.

B. Test Results with Oxygen and Water

We begin by presenting oxygen performance data collected for the WET-HET thruster with different discharge channel geometric configurations. For these tests, oxygen mass flow is kept to approximately 1 mg/s with a magnetic current of 1.5 A (this corresponds to approximately 600 G according to Fig. 4). The channel wall material used here is M26 grade Boron Nitride. The only fundamental difference between the two WET-HET configurations tested is the channel length: 34.8mm for the "Short channel" configuration and 13.1mm for the "Very Short channel" configuration. The naming choice for the channels stems from the fact that past oxygen experimental test campaigns revealed worse overall performance of the thruster for longer channel lengths [15]. Results from the "Short channel" and "Very Short channel" oxygen runs are shown in Fig. 10. The error bars in the measurements are calculated following the methodology presented in [16].

It can be seen from Fig. 10 that the use of a shorter channel ("Very Short channel") is beneficial for the thruster performance for most of the power range investigated (P_d = 600-1800 W). Thrust, specific impulse and anode efficiency (here referred to as "efficiency") increase when the channel becomes shorter. We posit this is because lower wall losses are experienced in shorter channels. At low power levels ($P_d \approx$ 700W), changes to the channel length do not seem to have a major effect on the overall behavior of the thruster.

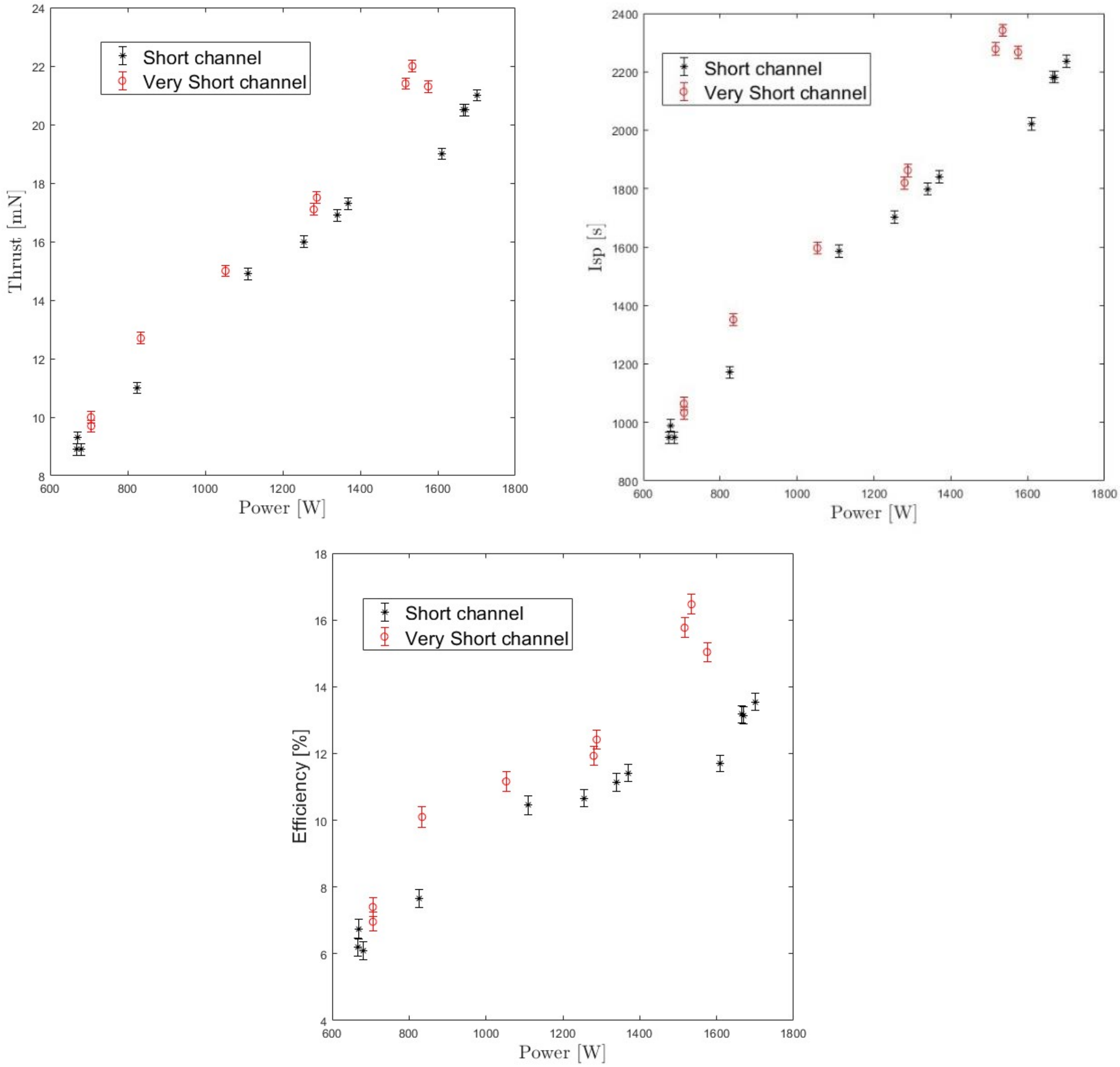


Fig. 10 Experimental measurements of thrust, specific impulse, and anode efficiency collected at the IPPL facilities using the modified WET-HE thruster, with oxygen propellant and a magnet current of 1.5 A

We then compare thrust, specific impulse, and efficiency of the thruster when operated with oxygen and water vapor (see Fig. 11). For this dataset, the thruster is tested using the same configuration: 13.1 mm channel length, 1 mg/s of propellant flow, and 1.5 A of magnetic current. We choose a channel length of 13.1 mm as this was the geometric configuration for which optimal performance was recorded. Under these conditions, it can be seen that oxygen performs better than water vapor overall for the power range investigated (P_d = 600-1800 W). When testing with water vapor, the plasma tends to be more fragile and unstable than with oxygen. As a result, water thrust measurements are more challenging and difficult to obtain.

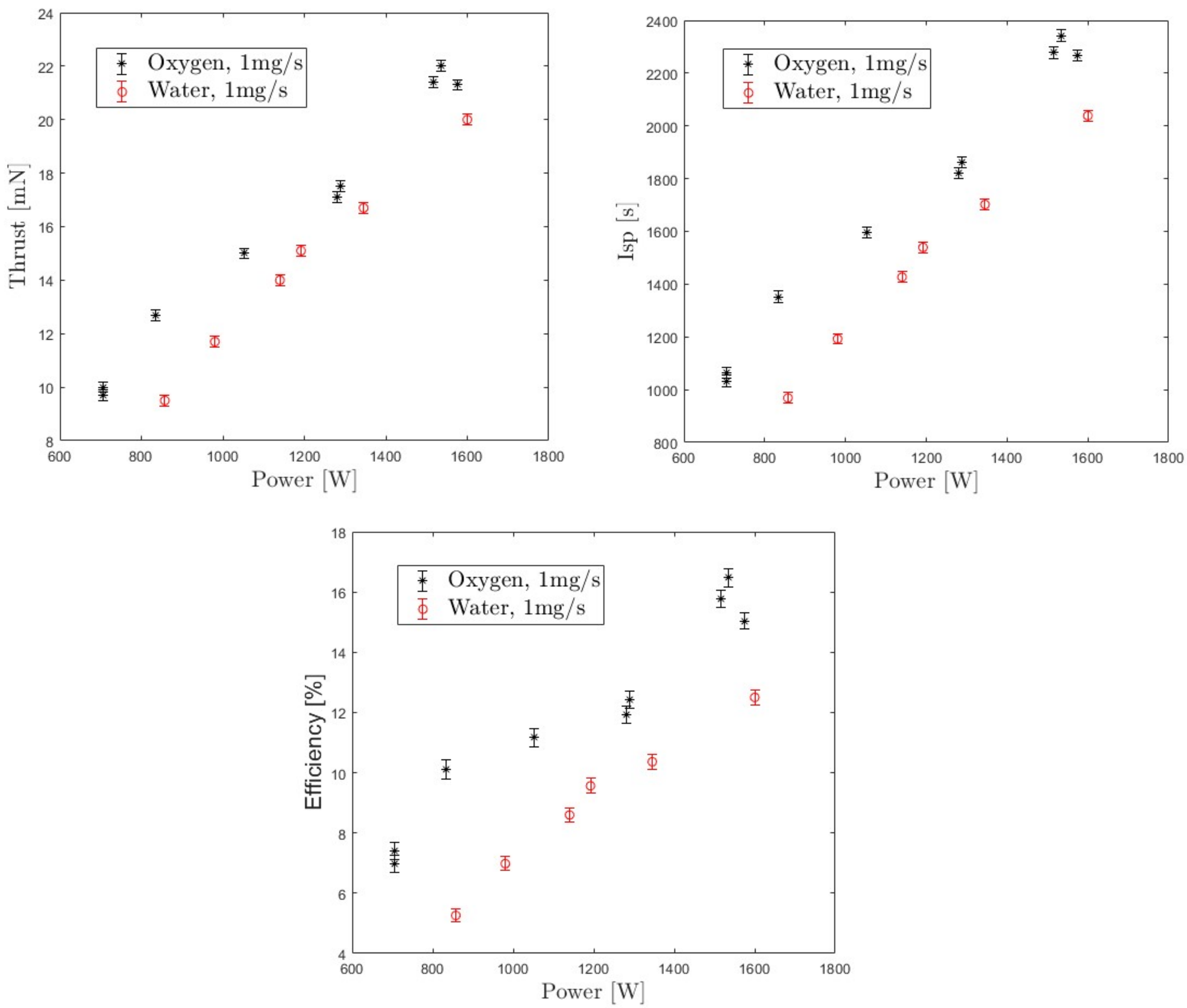


Fig. 11 Experimental measurements of thrust, specific impulse, and anode efficiency collected at the IPPL facilities using the modified WET-HET thruster, with oxygen and water propellant, a magnet current of 1.5 A, and a channel length of approximately 13 mm

Further experimental testing is planned to determine if water vapor can outperform oxygen at channel lengths shorter than 13.1 mm. The water feedline will be improved for this further testing to better measurement stability. Measurements will be collected using the new breadboard model AQUAHET thruster built with discharge channel sizes as determined in Section III. A description of the magnetic topology of this breadboard thruster can be found in Section V.

C. Comparison to PlasmaSim Predictions

Here we compare the PlasmaSim water predictions against experimental data points collected at the IPPL. The data points shown were collected at 1 mg/s of water flow and run through a modified WET-HET thruster fitted with a channel length of approximately 13 mm.

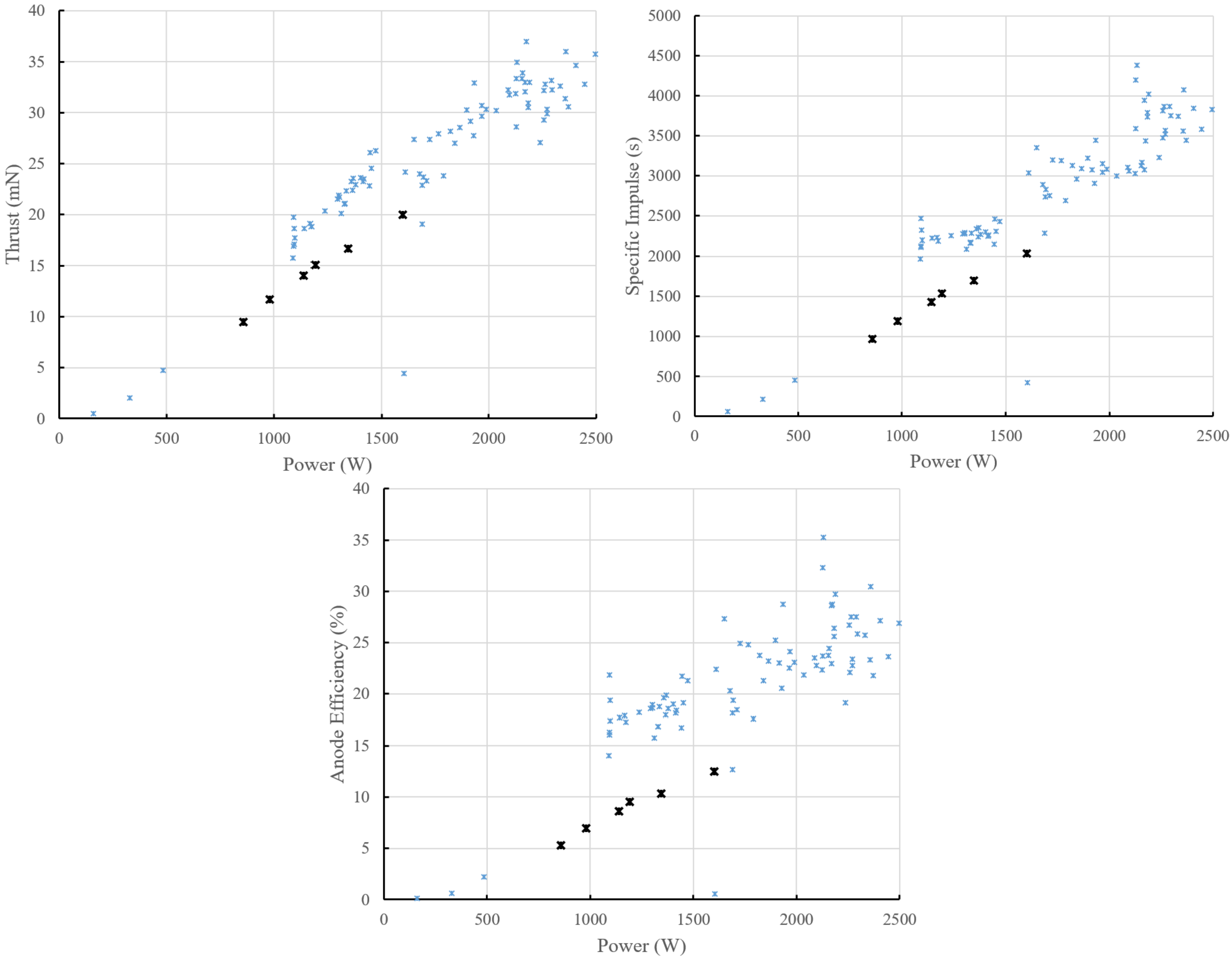


Fig. 12 In black: experimental measurements of thrust, specific impulse, and anode efficiency collected at the IPPL facilities using the modified WET-HET thruster running on water, with a magnet current of 1.5 A, and a channel of approximately 13 mm. In blue: estimated values of thrust, specific impulse, and anode efficiency as outputted by 1D PlasmaSim for a thruster running on water, with magnet currents in the 0.75-1.5 A range, and a channel length of approximately 13 mm

It can be seen from Fig. 12 that PlasmaSim is unable to accurately predict expected performance for the water fed AQUAHET. One approach to rectify this has been to attempt to include the effects of wall interactions [23]. However, this appeared to have little impact on the performance estimations for the water fed thruster, though it did improve the performance predictions of the oxygen fed thruster slightly. Another possible reason for the discrepancy is to do with collision modelling in the PIC-DSMC code. PlasmaSim only considers the first ionization and first dissociation cross-sections. For a semi-complex molecule like water, there are a large number of other modes of electron-neutron collisions possible with various cross sections [24] including a range of vibrational and rotational modes. Oxygen has some level of increased collision modes compared to xenon [25], but this is significantly less than that of water. The lack of capture of collision physics could be why the performance estimations for oxygen are significantly better than those of water and is something that future releases of PlasmaSim will implement.

V. Magnetic Topology Design of the 2-kW Water Fueled AQUAHET

While experimental data collected with a modified 13.1 mm channel length WET-HET laboratory model thruster did clearly show better performance for oxygen compared to water, there remain a number of geometric channel and magnetic configurations to be tested at with water vapor to optimize performance. We therefore proceed with the development of a modular AQUAHET with channel dimensions optimized for water. The second step in the conceptual design of the 2-kW level breadboard thruster consisted in determining the geometry/general sizing of the electromagnets. In keeping with the lessons learnt from the design of the oxygen WET-HET, we use a combination of an axisymmetric FEMM model and a ¼ symmetry COMSOL model for this phase of the design. The FEMM model is used for early-stage rapid iterations, while the COMSOL model is used for finalization of the sizing.

A. AQUAHET Magnetic Field Requirements

The WET-HET was built with an outer magnetic pole consisting of a stack of iron rings which could be raised or lowered to alter the magnetic thickness in the discharge chamber. Experimental thrust measurements taken using Imperial's hanging pendulum style thrust balance revealed optimal performance is achieved with oxygen as a propellant in the thinnest/'0-rings raised' magnetic configuration (see Fig. 3) [15]. This trend also generally holds true for xenon HETs. In a study carried out using a 1D macroscopic plasma model Ahedo et al. found that increasing the magnetic field thickness lengthened the acceleration region axially, thus increasing wall losses and so ultimately decreasing thrust efficiency [26]. We make the assumption this trend will remain accurate for a thruster operating with water vapor, and so set a requirement to have the shape of the radial magnetic flux density profile along the channel centerline follow a roughly Gaussian curve, with the peak situated as close to the channel exit as possible.

We have hypothesized that the non-radial components in the WET-HET channel field lines close to the exit plane is in part responsible for the preferential erosion of the inner channel ceramic walls observed during testing. As such, we set a requirement for the AQUAHET's magnetic field lines to be more horizontal close to the thruster exit plane.

B. AQUAHET Magnetic Topology

Using a combination of FEMM and COMSOL we arrive at the topology shown in Fig. 13 below. As can be seen from the plots, the field lines are much improved compared to the WET-HET, and the radial flux density has the required Gaussian shape.

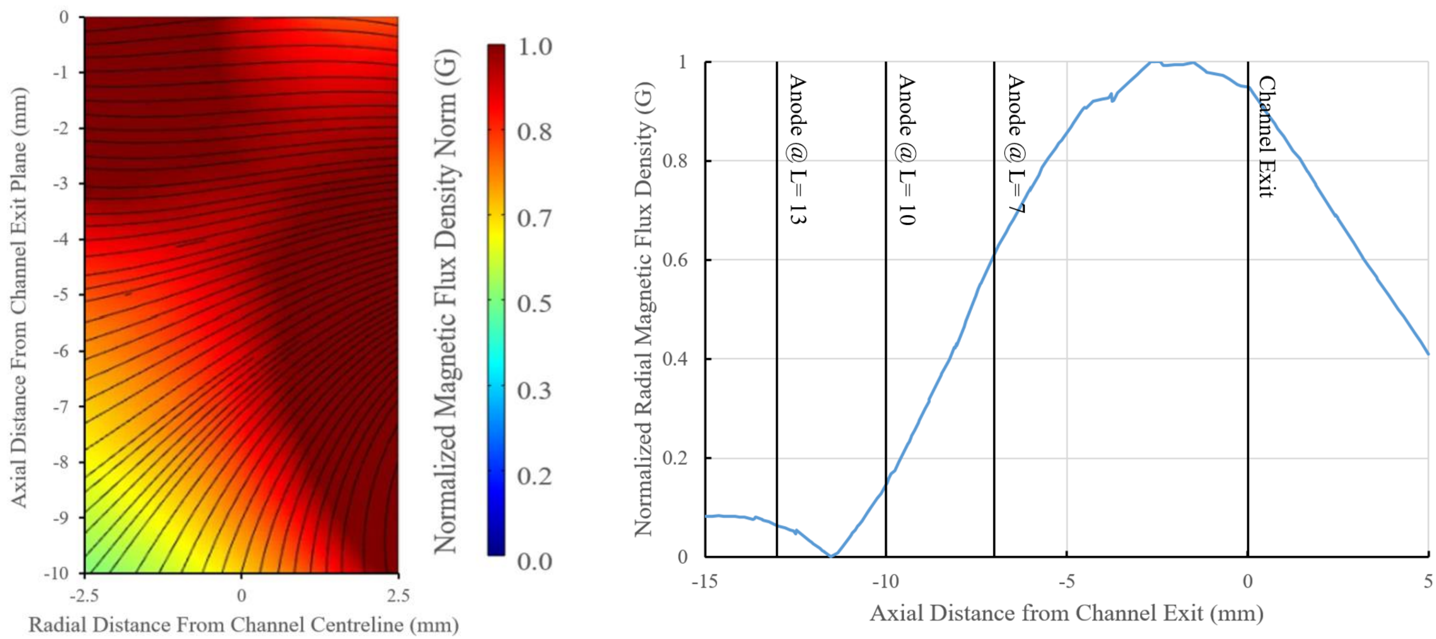


Fig. 13 On the left: Magnetic flux density norm in the channel along a cutplane, values normalized to the normB$_{max}$ On the right: Radial magnetic flux density along the channel centerline, values normalized to the radB$_{max}$

VI. Conclusions

The first step in the conceptual design of the 2-kW water fueled AQUAHET consisted in the sizing of the thruster's discharge channel. More specifically the channel length, mean diameter, and width. For this, we used Imperial College London's in-house fully kinetic PIC code, PlasmaSim. The version of PlasmaSim used in this work is one dimensional, includes ionizing dissociation, and has been shown to match well against oxygen experimental data. Despite this, we notice the presence of a number of high specific impulse / high thrust efficiency data points during the sizing runs for a 2-kW water vapor based thruster. This indicates the presence of a source of unaccounted loss in the code. A decision was therefore made to build a modular thruster which would allow for experimental testing of a range of channel geometric configurations. Channel lengths of 7, 10, and 13 mm; a channel mean diameter of 20 mm; and channel widths of 3, 4, and 5 mm are selected for the AQUAHET breadboard.

Previous work at Imperial College London on the development an oxygen fueled HET termed the WET-HET had highlighted the importance of having benchmark experimental data as early as possible in the thruster development life cycle to guide necessary improvements to our code. This, coupled with the presence of the high specific impulse data points during sizing runs, led to a decision to run an anticipated PlasmaSim validation test campaign. Existing WET-HET laboratory hardware was modified to fit a channel length of approximately 13 mm, a channel mean diameter of 20 mm, and a channel width of 5 mm. Thrust data is collected at the IPPL in the Boltzmann vacuum chamber facility using a hanging pendulum style thrust balance. Performance data measured for the L=13 mm channel configuration with 1 mg/s of oxygen is better than past oxygen data collected at L=35 mm. We measure thrust, specific impulse, and anode efficiencies of up to 22 mN, 2342 s, and 16.5% respectfully at L=13 mm with 1 mg/s of oxygen for discharge powers ranging from 710 to 1580 W. Water data collected at the L=13 mm configuration shows less favorable performance compared to oxygen. We measure thrust, specific impulse, and anode efficiencies of up to 20 mN, 2039 s, and 12.5% respectfully at L=13 mm with 1 mg/s of water for discharge powers ranging from 860 to 1600 W. This data is not in line with current PlasmaSim water predictions. We hypothesize that this is in part due to an inadequate capture of collision physics in the version of the code used.

The current mismatch between early water vapor experimental results and PlasmaSim sizing results further highlights the importance of building a modular AQUAHET breadboard thruster to allow for experimental optimization of the channel parameters. For the selected subset of lengths and widths, we use a mixed axisymmetric and ¼ symmetry modelling approach in FEMM and COMSOL to design an updated magnetic topology for the thruster. The magnetic field in the AQUAHET discharge channel features near horizontal field lines close to the channel exit plane and the radial magnetic flux density profile along the channel centerline follows a roughly Gaussian shape with the peak radial flux value occurring close to the channel exit.

Future work will include thermal simulations using a ¼ symmetry COMSOL model to ensure sound steady state operation of the breadboard thruster at powers of up to 2.5 kW. The AQUAHET thruster will then be manufactured and will undergo a second performance characterization test campaign in the fall of 2022 where the new hardware will be tested at a larger range of water mass flow rates, maximum radial magnetic flux density values, and channel geometric configurations.

Acknowledgments

This work was supported by the Eureka Association's Globalstars program with funding administered at the UK level of the consortium by Innovate UK, part of UK Research and Innovation. The authors thank Innovate UK for their continued support.

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