AQUAJET: AN ELECTRODLESS ECR WATER THRUSTER

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ABSTRACT:

We present the AQUAJET propulsion system, a cathodeless, ambipolar thruster test bed operating on multiple propellants including water. It is based on Electron Cyclotron Resonance (ECR) at 2.45 GHz using a simple permanent magnet configuration of the plasma source. We discuss the theoretical background of the technology, our flexible modular design that allows testing of many thruster geometry configurations, and modelling work done in preparation for testing.

1. BACKGROUND AND MOTIVATION

Electrodeless plasma thrusters using radio-frequency (RF) or ECR ion sources are being developed by many groups as next-generation electric propulsion systems ([1], [2], and references therein). They are ultimately expected to offer high exhaust velocities and performance without lifetime limiting erosion issues seen in gridded ion engines or Hall effect thrusters.

Using a microwave induced ECR heating mechanism allows the electron temperature to be significantly higher than levels attainable with RF discharge sources, potentially enabling better performance (c.f. [3]). The exhaust plume formed by ambipolar plasma expansion is quasineutral, eliminating the need for an external neutralizing cathode to maintain charge equilibrium on the spacecraft. The thruster is therefore both grid-less and entirely cathodeless. As these components are particularly fragile, their omission is expected to translate into longer thruster lifetime, higher reliability and a reduction of system cost and complexity (e.g [4]). Neutralizers are typically limited to a propellant choice of high purity noble gasses like Xenon. In contrast, a wide range of alternative propellants is accessible to ambipolar cathodeless thrusters, including molecular gasses like CO₂, O₂ and H₂O (e.g [5]). In the near term these propellants offer significant cost savings compared to Xenon. Water, the ultimate green propellant, is particularly safe for ride-share launches and allows light-weight tank design, as it does not require highly pressurised storage. In the long term the potential for combining these fuels with in-situ propellant production and in-space refueling from asteroids would be a fundamental breakthrough. Water-based smallsat thrusters are already reaching the market: COMET [6] and HYDROS [7] exploit electro-thermal and electrolysis technologies respectively, reaching specific impulse (Isp) of 180-310s. Theoretically, significantly higher Isp in the > 1000s regime can be achieved with an ECR ambipolar device and water propellant. We are working towards demonstrating this experimentally on a flexible laboratory prototype, and assessing the achievable thruster efficiencies over a wide power range (10-200 Watts) via direct thrust measurements.

ECR is a technology commonly used in ion sources for particle accelerators where AVS has a strong heritage, developing state of the art systems and manufacturing devices used in several European linear accelerators. AVS is a new player in electric propulsion, building on this experience. The AQUAJET project is a collaboration between AVS, the University of Surrey and STFC, with funding from the UK Space Agency. Due to its key benefits for an overall propulsion system in terms of cost, safety and tank mass, we are initially focussing on water propellant. We are benchmarking this against argon, a widely used propellant in laboratory experiments on cathodeless thrusters.

2. PREVIOUS WORK

To date, RF plasma thruster development has been beset by low performance, particularly in terms of thruster efficiency which often remained at the ≤1% level [1]. Improvements towards the ~10% level were then reached, e.g. in [8] at high (2 kW) power levels, with Isp of order 2000s. A breakthrough at low power levels of order 50W was achieved with a coaxial ECR plasma thruster developed by the ONERA lab ([2],[9] and references therein): efficiency of around 13% at 1 mN thrust and Isp of 1300s, using Xenon. Work is ongoing by the MINOTOR consortium [3] to improve this device, expanding its operating
envelope and conducting further geometry optimisation of the prototype. Laboratory prototype testing of RF and ECR thrusters has predominantly used noble gas propellants (Argon, Xenon and Krypton) to date. Molecular propellants such as water are significantly more complex than noble gasses, with many additional plasma species (including negative ions) and electron-molecule interactions, e.g. dissociation, dissociative electron attachment, vibrational & rotational excitation. Several molecular propellants (CO₂, N₂, O₂, CH₄, and others) for electrodeless thrusters were tested in [5], achieving ISP > 1000s. Theoretical thruster geometry optimisation with different molecular propellants in [10] predicted optimum performance for N₂O. Neither of these works assessed water propellant.

A comprehensive overview and theoretical analysis of water plasma in the context of electrodeless thrusters has been published in [11]. The analytical calculations consider all relevant interactions and electron energy loss pathways as a function of Maxwellian electron temperature $T_e$. The key conclusions and predictions in this work are that:

- the plasma is electropositive (negative ions play a negligible role) and completely dominated by H₂O⁺ ions
- additional loss pathways lead to an ionization cost far larger than that of argon at low $T_e$
- the H₂O ionization cost and predicted thruster efficiency is extremely similar to the argon case if electron temperatures above 5 eV are reached

This is promising, and requires experimental confirmation which to our knowledge has not been published to date.

3. PHYSICS OF ECR ELECTRODELESS THRUSTERS

In the case of a coaxial configuration, the cylindrical thruster chamber includes a central antenna along its axis, and both these metal components are connected to the coaxial line from the microwave generator (Fig.1).

Neutral gas is injected into the chamber, and a high density plasma is created by efficient free electron heating via the ECR effect and inelastic electron-neutral collisions. The chamber is immersed in a magnetic field that reaches 875 Gauss. Free electrons gyrating along the field lines will then satisfy the ECR condition at an input frequency of 2.45 GHz, and continuously absorb microwave energy. Note this frequency is used primarily because it is the most widespread microwave generator frequency. The axial magnetic field divergence along and beyond the chamber (“magnetic nozzle”) causes acceleration of electrons down the chamber axis, and an ambipolar field is set up that accelerates the ions. Both stream out of the chamber at high velocities, maintaining a quasi-neutral exhaust plume. Unlike other ECR sources used in e.g. gridded ion engines, ambipolar thrusters do not rely on a separate ion extraction system. Ambipolar plasma flow out of the chamber is enabled purely by the magnetic field geometry. Downstream of the chamber, detachment of the plasma from the field lines occurs, and thrust is therefore generated.

As a collisionless plasma can be assumed at the relevant densities, the remaining neutral gas fraction should experience little heating and contribute negligibly to thrust. For ambipolar ECR type thrusters, the magnetic field geometry is constrained by the multiple critical functions it performs:

- plasma source: the resonant field strength of 0.0875 Tesla at the 2.45GHz microwave frequency must be reached across a flat ECR zone, close to the backwall of the thruster. The surface should not touch the backwall, to reduce plasma losses.

- radial plasma confinement: the field must be oriented axially down the thruster: limited radial cross-field plasma diffusion results in lower losses to the radial walls.

- axial plasma confinement: a magnetic mirror effect should be created at the backwall to limit plasma losses to that surface. Throughout the chamber, the axial component of the magnetic field strength should therefore increase towards the backwall.

- magnetic nozzle: downstream of the chamber, the field should continue to diverge, decreasing in strength axially, in order to form a magnetic nozzle.

All of these conditions can be met with a simple solenoid electromagnet, however the required current of order 100 A precludes a flight-like design. Instead, annular permanent magnets mounted behind the chamber can be used to create the desired magnetic field.
4. ANALYTICAL MODEL & CONCEPTUAL DESIGN

A full physics numerical model of electrodeless ECR thrusters is extremely challenging. The problem covers the coupled ionization and acceleration region within a magnetized flowing plasma in the chamber, the microwave-plasma coupling, and downstream detachment. This is still the subject of active research in the literature, and we are not aware of any publications describing successful full numerical models of such thrusters. While lacking a full numerical model, we chose a pragmatic approach, using the simple analytical model framework of [1] & [2] to roughly constrain the thruster geometries of interest with both argon and water propellant. We then designed a highly flexible modular thruster testbed for experimental, parametric tests of the chamber geometry, as also done in [9]. We do not expect this simple model to predict thruster performance with high accuracy, but to at least capture performance trends across chamber geometries.

4.1 Permanent magnet

We are using a Samarium-Cobalt permanent ring magnet with a remanence of 1.08 Tesla. Following initial thruster chamber sizing, we used FEM software to find a magnet geometry satisfying the requirements described in Section 3 and with a large enough inner diameter for the attachment of a coaxial cable and connector (c.f. Fig.1). We avoided excessively large magnet dimensions as its mass would become prohibitive for use in a future flight-like design. The final properties of our annular magnet are: inner diameter 20mm, outer diameter 50mm, height 20mm, mass 280g. The magnetic field configuration and ECR zone of this magnet are shown in Fig.2.

4.2 Analytical model

The model was originally derived for helicon RF plasma thrusters by [1], and was adapted to coaxial chamber configurations by [2]. Reasonable agreement with experimental results on both types of thrusters was shown. The model takes into account the plasma source region and the magnetic nozzle out to detachment. The model is quasi-one-dimensional, determining the plasma density and neutral gas density along the length of the thruster by solving the relevant continuity, momentum and energy conservation equations and self-consistently computing $T_e$, wall losses, ionization fraction (i.e. mass utilization efficiency $\eta_m$), ion velocity, thrust, $I_{sp}$ and thruster efficiency $\eta_t$. Microwave-plasma coupling is not included in the model; we follow the approach in [2] of simply assuming a (constant) coupling efficiency, in our case 100%. We also adopted an ion temperature of 0.2 eV, a neutral gas injection velocity at the speed of sound of the relevant propellant (at room temperature), and the argon ionization rate factor as a function of $T_e$ from [12].

Figure 2: Cross-sectional view of the magnetic field configuration (top; field lines in white) and ECR zone location (bottom, in blue). The AQUAJET thruster chamber with a 10 mm radius and an antenna with dielectric sleeve are shown (black outlines). The permanent magnet location is mostly out of view at the bottom of both plots.

We computed an empirical fit to the ionization rate factor for $e^- + H_2O \rightarrow 2e^- + H_2O^+$ by using the relevant cross-section dataset given in [13], and assuming a Maxwellian electron energy distribution function. We used the relations in [11] to calculate the ionization cost as function of $T_e$ for both argon and water. The other key inputs to the model are the magnetic field strength in the source region and at the chamber exit plane for the geometry described in Section 4.1; input power; the chamber length $L$ & radius $R$; and the mass flow rate $\dot{m}$.

We ran the model over a large grid of the latter three variables for both argon and water and an input power of 30-200W, covering $\dot{m} = 0.1 - 0.4$ mg/s, $R = 5 - 14$ mm and $L = 5 - 50$ mm. Results over this parameter range and peak predicted performances are summarised in Tab. 1. Highest $\eta_t$ and $I_{sp}$ for argon and water were predicted to occur over $R = 8-12$ mm, $L = 6-8$ mm and $\dot{m} = 0.1-0.4$ mg/s. For our modular testbed design
described fully in Section 5, we therefore manufactured three chamber radius configurations \((R = 8; 10; 12 \text{ mm})\), with adjustable chamber lengths in each case.

### Table 1: analytical model predictions.

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<th>H(_2)O</th>
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<tr>
<td>(T_e)</td>
<td>10-20 eV</td>
<td>10-60 eV</td>
</tr>
<tr>
<td>(\eta_m)</td>
<td>3-25%</td>
<td>10-70%</td>
</tr>
<tr>
<td>Peak (\eta_i)</td>
<td>6%</td>
<td>14%</td>
</tr>
<tr>
<td>Peak (I_{sp})</td>
<td>900 s</td>
<td>2000 s</td>
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<tr>
<td>thrust</td>
<td>0.6-3 mN</td>
<td>1.5-4.5 mN</td>
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Note the worse predicted performance for water propellant is primarily due to a significantly lower mass utilization efficiency caused by the lower ionization rate factor of H\(_2\)O compared to argon over the relevant electron temperatures.

### 4.3 Antenna design

As part of our modular test programme, we are assessing two antenna designs: in one case, the antenna is covered by a dielectric “sleeve” (Fig. 2) and in the other the metal antenna is directly exposed, with the dielectric covering only the chamber backwall. The latter is expected to be more prone to life-limiting erosion in a water plasma. Therefore our baseline design is the sleeve option, however we will assess differences in thruster performance between the two cases through direct thrust measurements.

To achieve plasma ignition, it is important to reduce the mismatch between the 500 coaxial line from the microwave generator and the (vacuum) impedance of the thruster and at the same time maximise the electric field strength near the ECR zone. Following the chamber sizing described above, we set up electromagnetic frequency-domain models of the various chamber-antenna systems using multiphysics software. Our goal was to optimise the antenna and dielectric geometry for all 3 choices of chamber radius and the 2 antenna design options, in terms of impedance mismatch and electric field strength. We maximised the latter at a reference point 2 mm above the chamber backwall, and imposed a condition of thruster impedance ≤ 200 Ω.

In the models with an antenna dielectric sleeve, the optimisation variables were those shown in Fig.3. All other thruster chamber geometry values were fixed to follow the results of 4.2 and to allow compatibility between parts and straightforward assembly of our modular design. As part of this optimisation we considered Alumina and Boron Nitride (BN) as the dielectric material. Significantly better results were achieved with BN due to its much lower permittivity, \(\varepsilon_{\text{BN}} \approx 4.0\) versus \(\varepsilon_{\text{Alumina}} \approx 9.5\). The water propellant used in AQUAJET required us to select BN grades using a SiO\(_2\) binder that are moisture-resistant. BN can be machined into the required shapes including the “sleeves”, unlike quartz which has often been used as the dielectric in previous plasma thruster testing.

![Figure 3: Chamber-antenna model geometry for \(R=10\) mm, with the dielectric (blue) covering the metal antenna.](image)

Note BN has been used to cover only the backwall of the thrusters tested to date for MINOTOR (Sect.2), and this material has extensive electric propulsion flight heritage in Hall Effect thrusters.

### 5. MODULAR TEST-BED DESIGN

As discussed above, we required the capability to parametrically test a range of thruster geometries due to the limitations of our analytical modelling. Our flexible design allows exchanging different chamber radii, varying the chamber length, adjusting the ECR zone position, and the antenna properties. Fig.4 shows our AQUAJET design in the configuration with a chamber radius of 8 mm. Apart from the dielectric and copper antenna, all machined parts are made from aluminium, preventing any issues with the strong permanent magnetic pull-force in (re-)assembly. The annular permanent magnet (a) is placed into a magnet housing (b). Three washers (c) are bolted to (b). Several sets of washers with different heights are available: exchanging these shifts the distance between permanent magnet and thruster chamber, i.e. the ECR zone location. This will allow confirmation of the result in [14] that the minimum ECR-backwall separation leads to optimum performance.

A TNC coaxial female – male connector pair (d) and cable (e) assembly with the soldered copper antenna (f) is attached to the thruster baseplate (g). The dielectric (h) is placed over the antenna and held in place by the chamber wall component (i). The chamber length can be varied in steps of 2 mm by adding extensions with different heights (j). Based on our analytical model, length extensions are predicted to facilitate plasma ignition, but cause lower thruster performance via increased plasma wall losses. This needs to be validated experimentally. Parts (f, h, i, j) are exchanged.
when different chamber radii are being tested. Three brass NPT 1/16" Swagelok fittings (k) of the radial propellant feedlines are attached to the chamber wall. The entire AQUAJET testbed is bolted to a thrust balance using (l). We manufactured sufficient modular components to simultaneously assemble 2 AQUAJET thruster configurations with different chamber radii. This allows quick “swapping” of thrusters during the test campaign, reducing time losses.

6. EXPERIMENTAL SETUP

AQUAJET is being tested in the Daedalus electric propulsion facility at the Surrey Space Centre (SSC). The vacuum chamber presents a diameter of 1.5 m and a length of 2.5 m. The pumping system includes a cryogenic and a turbomolecular pump in parallel, with an overall pumping capacity of 12000 l/s (air), giving a background base pressure of 7x10^-7 mbar without flow injection. Pressure levels in the chamber and pumping lines are monitored via multiple gauges and feedthroughs are provided for sensor signal lines, power and propellant feed lines. The propellant flow is regulated through calibrated mass flow controllers.

The thruster testbed is powered by a Kuhne Electronics signal generator (KU SG 2.45-250A), providing adjustable power from 10 to 250 W over a 100 MHz bandwidth centred on 2.45 GHz. This generator includes an isolator and measures forward and reflected power.

We ensure zero net current flow from the thruster by including a DC block on the microwave line, and by mounting it to the thrust balance structure via ceramic isolators. A bias tee between DC block and thruster monitors the potential at which AQUAJET is floating.

To collect direct thrust measurements, we have mounted AQUAJET to a pendulum type thrust balance. The force generated by the propulsion system induces a displacement of a movable hanging platform, measured by a laser sensor (Micro Epsilon ILD 1700-2) with a resolution of 0.1 μm. The displacement d is linearly dependent on the thrust T multiplied by the system’s equivalent stiffness, the calibration factor C. Multiple calibration force increments are implemented via calibration masses, a rotational stage and pulley system. Calibration is performed in vacuum with the thruster mounted in the same way as during firings, to include the stiffness of all feedlines. We estimate the uncertainty on C using a Monte Carlo approach and account for thermal drift and propellant feedline pressurization effects on the thrust balance output.

We use a Faraday probe to measure angular current distribution (plume divergence) and a Langmuir probe to characterise T_e, ion density and plasma potential.

7. CONCLUSION AND OUTLOOK

An overview of the cathodeless, water propelled, ambipolar AQUAJET propulsion system was given. We explained the motivation for developing such a thruster using water propellant and ECR at 2.45 GHz in particular, and the need for a flexible prototype testbed. Our design allows varying the thruster chamber’s radius, length and the ECR zone’s position within it, and it enables the use of
both metal and ceramic-covered antennas. We optimised all antenna geometries in terms of electric field strength at the ECR zone and the thruster's vacuum impedance. The simple annular permanent magnet configuration of AQUAJET was explained. We described the basic analytical modelling done to constrain the parameter space for testing of different chamber configurations, and the experimental setup that is being used to characterise the thruster via direct thrust measurements. Our analytical model predicts significantly worse performance for water propellant compared to argon due to the lower ionization rate factor. We will verify this prediction by testing AQUAJET with both propellants, and are experimentally determining the optimum thruster geometry and actual performance achievable.

8. ACKNOWLEDGEMENTS
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9. REFERENCES