Design and Testing of a Micro-to-Milli-Newton Pendulum Thrust Balance for Indirect Thrust Measurement

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ABSTRACT

THE performance of an indirect pendulum thrust balance suitable for micro-Newton level thrusters is presented. A design based on a frictionless pendulum with a laser optical lever and detection system makes it possible for thrusters to be mounted independently of the thrust measurement system. This simplifies the process of calibration without having to compensate for electrical connections, flow lines and other equipment. Measurements are not limited by thruster mass and offer thrust measurements down to 80μN. The balance was demonstrated by measuring the performance of two micro propulsion devices; the T5 and T6 hollow cathode thrusters. The T5 generating thrusts from 0.1mN to 1.4mN and the T6 showed thrusts from 0.2mN to 1.9mN.

INTRODUCTION

PROVIDING in-house capability to resolve thrust in the sub-milli-Newton range is essential to the ongoing development of hollow cathode micro-thrusters at the University of Southampton. Thrusts in the tens or hundreds of milli-Newtons can be made with direct measurement rigs and the use of flexible propellant tubing and thoughtful electrical connections. As sub-milli-Newton thrusts are approached direct thrust measurements are disturbed by thermal drifts, facility noise and mechanical stress from propellant and electrical connections which can be on the order of the thrust level. Several methods have been used in the past to characterize microthruster performance. The most accurate method is the direct thrust measurement approach and has been developed by a few actors including ARC Siebersdorf[1], Busek and NASA Goddard[2], and NASA JPL,[3] however the effort to combat calibration shifts requires active closed-loop compensation mechanisms which significantly increases complexity. Separating a thrust stand from the thruster assembly as shown in Figure 1, so that only the ejected propellant impinges on the balance enables the measurement of momentum transfer independently of the thruster assembly, thus limiting some sources of noise and calibration shifts. Indirect thrust measurement does bring unknowns such as the mechanism of momentum transfer to the balance however its simplicity of operation and the fact that this unknown can be quite reasonably be assumed or experimentally derived advocate the development of such a thrust balance.

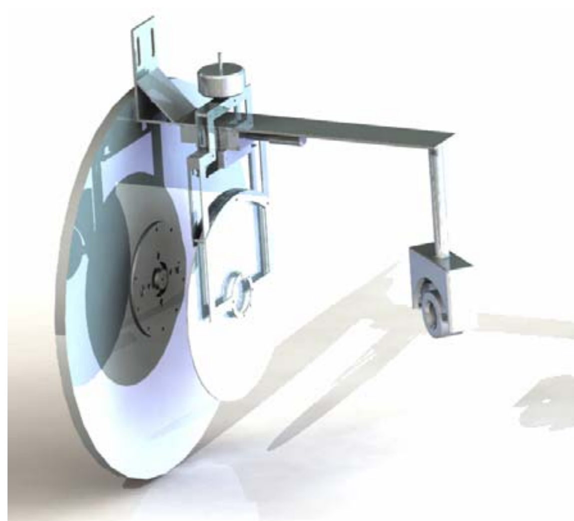

Figure 1 CAD Design of the in-direct pendulum

Hollow cathodes may represent an attractive propulsion device for a number of reasons. Spacecraft which operate primary electrostatic or electromagnetic propulsion systems such as gridded ion thrusters and Hall thrusters are typically required to carry a secondary chemical system for reaction/momentum control or to compensate for thrust misalignment.[4 5 6 7] These secondary systems constitute a large fraction of the overall propulsion system mass while they are only required to produce a small fraction of the total impulse. These systems also bring substantial cost increases in manufacture, assembly, integration, test operations, and launch preparation primarily due to hazardous propellants.[8] A simpler solution would be to use a moderate performance secondary system able to operate from a common inert propellant with the primary system; however the high molecular mass of xenon limits the performance of cold gas thrusters and resistojets to between 15-60s specific impulse. [9 10]

Previous testing at the University of Southampton on the T6 hollow cathode has shown that at least a basic thruster can be formed, generating moderate specific impulse (<300s with xenon) at thrust levels <2 milli-Newtons using a cantilever beam thrust balance.[11 12 13] The most likely thrust mechanism was determined to be from electrothermal type operation with propellant expulsion at relatively high pressure. Thrust resolution and accuracy was compromised during these early tests by a number of issues. Firstly no form of damping was applied to the balance causing a loss of resolution due to external excitation. Secondly, thermal drifts due to the differential heating of the target and beam complicated measurement and compromised accuracy. Furthermore, thrust measurements in the noisy hollow cathode 'plume' mode also excited the balance and deteriorated resolution. This work aims at production of a system capable of more reliable and accurate thrust measurements.

T5 and T6 hollow cathodes are a mature technology developed extensively over the last 35-years for application on the UK-10, UK-25, T5 and T6 gridded ion thrusters [14 15 16 17 18 19] and as an electron source for various ion beam neutralization applications. [20] The low operating power of hollow cathode such as the T5 (<90W) may also present a microthruster suitable for smaller satellites (<150kg).

Guidelines issued by the Inter-Agency Space Debris Coordination Committee (IADC) recommend that spacecraft in low earth orbit have the ability to deorbit within 25-years. This increases the mission delta-V by some 100-500% for typical earth observation missions.[21] As demands on small spacecraft also continue to grow for missions such as formation-flying, inspection and rendezvous, requiring drag compensation, constellation phasing and proximity maneuvering,[22] conventional robust microsatellite propulsion systems such as cold gas thrusters and resistojets are deficient in performance. Microsatellite platforms however lack the resources to support advanced enabling technologies such as micro-ion engines and Hall thrusters. The diffuse arc in the T5 hollow cathode in particular permits operation at convenient discharge voltages (10-25V) for satellites with limited power electronics, especially when compared to other electrothermal, electrostatic or electromagnetic thrusters. [23] Furthermore a hollow cathode microthrusters system would able to draw from existing inert propellant storage and feed architectures for conventional cold gas/resistojet systems which find considerable use on small satellites due to their simplicity and low cost nature. This makes their addition a reasonably simple process. Hollow cathode thrusters may therefore be a fitting compromise if their performance is sufficient.

EXPERIMENTAL APPARATUS

Optical Thrust Measurement System

Optical setup consists of a Miles Grilot He-Ne (543.5nm) laser passed through a Keplerian beam expander and directed through the chamber onto a mirror, rigidly connected to a molybdenum pendulum target shown in Figures 2 and 3. The optics system guides the reflected beam out of the chamber and onto a Hamamatsu 4.7 x 4.7mm two-dimensional

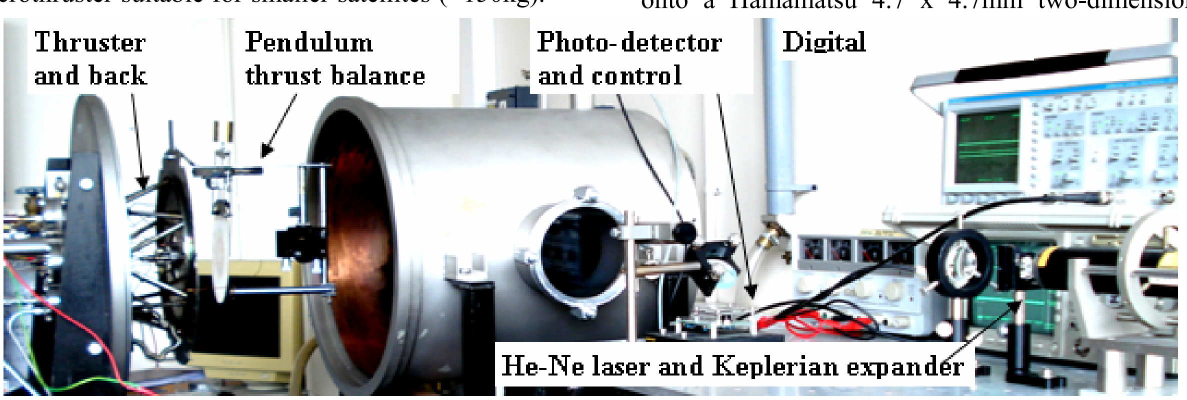

Figure 2 Experimental setup

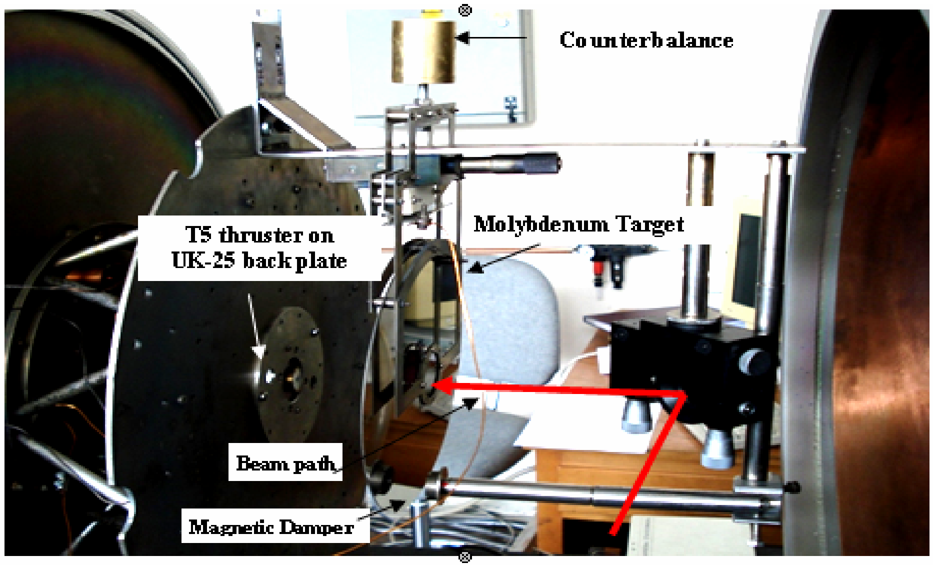

Figure 3 Pendulum thrust balance assembly

tetra-lateral photo-sensitive-detector (resolution of 600nm) at a path length of 1,132mm. The detector is coupled with a C4674 signal processing circuit (output +/-2.5V at 1V/mm on each axis) is designed to provide two-dimensional position data on the incident light spot independent of the light intensity and is powered by a 30V Instec dual-tracking power supply (ripple less than 3mV). The output from the signal processing circuit is displayed on a Tektronix TDS 410A 2-channel digital oscilloscope (resolution +/-0.001V). A pivoting mechanism allows the target to be positioned both perpendicular to the thrust vector and through a full 90˚ sweep of angles, while also allowing the pendulum to be electrically floated, grounded or biased.

The pendulum thrust balance is mounted on a beam fixed to the UK-25 ion thruster back plate and is positioned with the cathode on axis with the centre of the target. The stand-off distance between the pendulum target and the thruster can also be set between 20-250mm and micro-translation mechanism is used to finely adjust the position of the target. Unwanted oscillations in the system are passively damped by eddy current induction of a weak magnet placed close behind the Molybdenum target, electrically dissipating energy in the system. The optical detection setup of a green He-Ne laser mounted externally, two convex lenses forming a Keplerian beam expander and four mirrors.

The pendulum assembly was designed in a sandwich structure to give a high degree of rigidity whilst being designed symmetrically to minimize any geometrical changes due to thermal effects. Initially the molybdenum pendulum target was polished to a mirror finish on both sides to enable the measurement beam to be directly reflected off the rear of the target, however even with an optical finish noise generated by small imperfections in the molybdenum generated excessive signal error and an additional piece of the pendulum assembly was manufactured to enable the an optical quality mirror to be held in place behind the target.

Since the returning spot size is approximately 0.5mm the maximum allowed displacement was set to 2mm, 40% of the total possible displacement. A representation of the optical path is shown in Figure 4. Since the sensor delivers a signal independent of the light intensity but rather up to a threshold intensity (essentially a hi-pass filter) it is important to fully collect the returning signal. The selected sensor displacement range thus ensures that all of the light from the returning spot falls on the sensor given the maximum expected thrust.

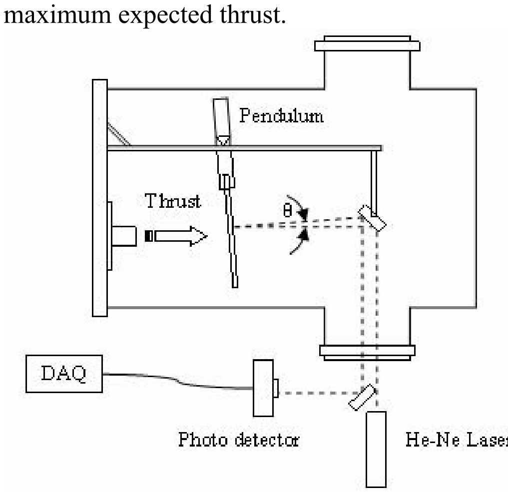

Figure 4 Representation of the optical path

Similarly in this way thrust resolution can be traded for thrust range by selection of an appropriate counterweight, extending or shortening the optimal thrust range. Fine positioning of the spot is provided by manipulation of an optical mirror mounted directly above the sensor. Some parameters required for the exact selection of the counterweight were:

- Maximum expected thrust (3mN)
- Sensor traverse available (4.7mm)
- Maximum allowed detector displacement (2mm)
- Path length from detector to target (1.323m)

For a small angle deflection where the path length is much larger than the sensor displacement length (L_p>>L_s) the maximum tolerable angle of deflection of the balance (θ_{max}) can be defined by the available sensor displacement, given by:

$$\vartheta_{\max} = 0.5 ArcTan\left(\frac{L_p}{L_{s\max}}\right)$$

where L_{smax} is the maximum allowable sensor traverse. The balance force (F_{CT}) acting down through the centre line required for equilibrium at θ_{max} is given by:

$$F_{CT} = \frac{T_{\max}}{Tan\,\vartheta_{\max}}$$

where T_{max} is the maximum expected thrust level. The subsequent thrust measurement can be calculated in the same way by knowing θ and thus the signal displacement on the sensor. A test rig was developed to precisely balance the pendulum for calibration and sizing of the counterweight. The test rig is shown in Figure 5.

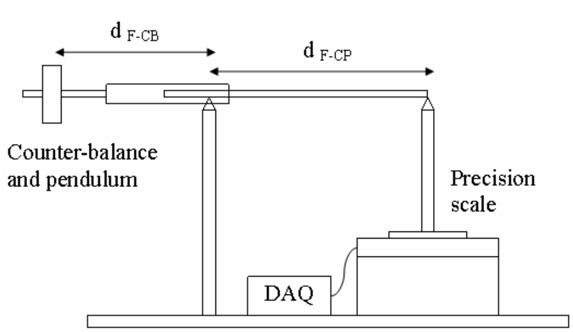

Figure 5 Representation of the pendulum calibration rig

The necessary counter weight (M_{CB}) required to give θ_{max} at the maximum allowable photo-sensor displacement (L_{smax}) is found by:

$$M_{CB} = \frac{F_{CP} d_{F-CP}}{d_{F-CB} g_0}$$

Where d_{F-CB} is the distance from the distance from pendulum fulcrum to the pendulum counter-weight centre point and d_{F-CP} is the distance from the pendulum fulcrum to the scale calibration point.

Vacuum Rig

The vacuum rig used in this experiment is described in [24] previously used for hollow cathode characterization within the UK-25 ion engine. The rig consists of a 500mm diameter by 500mm long chamber with ISO and CF flanges. Three main ISO 160 ports allow connection of the pumping system with view ports on either side of the vacuum chamber allowing optical access. Four CF35 ports integrated into the ISO500 door flange allow feed-through access. Pressure gauge heads are located in KF25 and KF40 ports on top of the chamber. A cylindrical water cooled copper shroud fitted around the inside of the vacuum chamber wall is used to dissipate heat load with the water feed-through entering from a CF35 port at the blank end of the chamber.

Pumping is achieved with a water-cooled turbo molecular pump (Pfeiffer Balzers TPH 520KTG, 500l/s) controlled by a TCP 380 power supply (with a TCS303 pump control unit) and backed by a rotary vane pump (Edwards EH500A H/C 80 CMH), achieving an ultimate vacuum of 10^{-8} mbar. This level of vacuum ensures the partial pressure of oxygen in the system is low enough to prevent poisoning of the chemically sensitive thermionic emitter. Propulsion grade argon (99.997% pure) is passed through high and low capacity oxygen traps via an Edwards FCV10K extra fine control needle valve. Vacuum pressure is monitored with a Balzers TPG300 pressure gauge package constituting a pirani (1000-5.4x10^{-4}mbar) and cold cathode gauge head (5x10^{-3} – 1x10^{-9}mbar). Prior to operation the cathode was allowed to outgas at a pressure <1x10^{-6}mbar for 2-days. After this outgassing the heater was operated at a current of 0.5A for 24 hours. This ensured that the flame sprayed heater ceramic is well outgassed and therefore the chances of the heater failing are dramatically reduced.

The propellant supply system is designed to be flexible and accommodate a large range of flow rates for full thrust characterization of the T5 and T6 cathode. A Spectra Gasses 7120 high accuracy double-stage regulator supplies propellant to the feed system. A sampling cylinder (bypassed during experiment) and Druck PDCR910 pressure transducer are used for flow calibration before each round of testing with a repeatability of better than 4%. All external feed lines are above atmosphere pressure to reduce the possibility of air leaks into the flow system.

Power Supplies

The typical T5 gridded ion thruster from which the T5 hollow cathode is derived comprises nine independent supply units to power various elements of the system. In operation of the T5 and T6 cathode as a stand-alone thruster, the number of power supplies is reduced to three. It is also worth noting that since the cathode is in effect self-neutralizing, there is no need to electrically float the thruster system to a high positive potential, removing the requirement for electrical isolation of the thruster mounts and propellant feed lines. The electrical wiring system inside the chamber is also designed to minimize the influence of any MHD effects on the plasma both within the cathode and on the externally emitted plasma which may influence the thrust vector.

The power supply system used to operate the T5 hollow cathode is shown schematically in Figure 6. The cathode heater supply (Powerbox Lab605) provides the 2.2A required to heat the cathode to ignition temperatures (>1000˚C) prior to discharge ignition. The heater supply is operated in constant current mode with a common ground to the cathode potential to minimize the voltage difference between the heater wire and cathode body, reducing the risk of heater insulation breakdown. The discharge power supply consists of a high voltage (1kV, 30mA) strike supply and a low voltage (80V, 37A) steady state supply protected by diodes.

The strike voltage is supplied by a pair of Farnell Hivolt PM1/DCP photo-multiplier supplies connected in parallel and powered by a pair of Farnell 16RA24012 linear 24V power supplies. Once the discharge is initiated, steady state power is provided by a Glassman LV80-37 DC power supply. This is a 3kWswitch mode supply with load regulation of +/-0.1% and an output ripple of 10mV RMS over the frequency range 20Hz-20MHz. Plasma noise and instabilities in the discharge are monitored with a Gould 1600 digital oscilloscope connected across the anode power supply. Anode voltage current characteristics are monitored via the supply digital meters, limiting the resolution of the readings to +/- 0.1A and +/- 0.001V, while strike voltage was monitored by a digital multi-meter with a resolution of +/-0.001V.

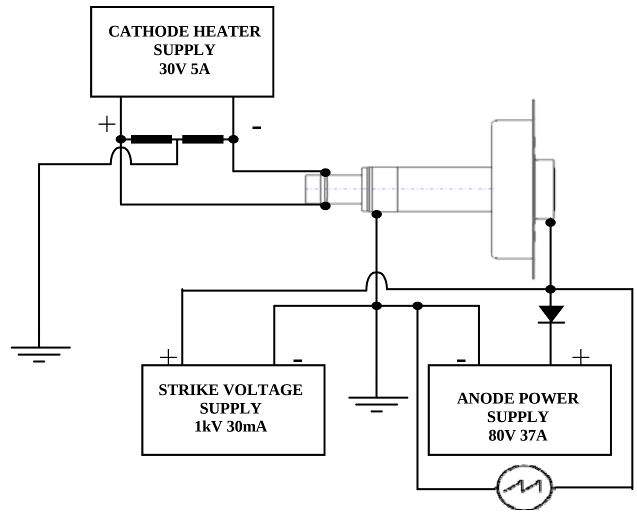

Figure 6 Electrical setup schematic

RESULTS AND DISCUSSION

Cold Gas/Resistojet Thrust Measurement

The hollow cathodes can be operated in a cold gas and resistojet mode (with the cathode heater only operating) in addition to the discharge mode. Tests were conducted with argon for the T5 and with argon and xenon for the T6 cathode to characterize possible performance in these two modes and give some indication of the degree of elastic or non-elastic collisions with the target. Figures 7 and 8 show the thrust and specific impulse obtained when operating in a cold gas and resistojet mode. During the heated mode, the T5 cathode was operated at 19.7W heater power with the T6 operated at 50W.

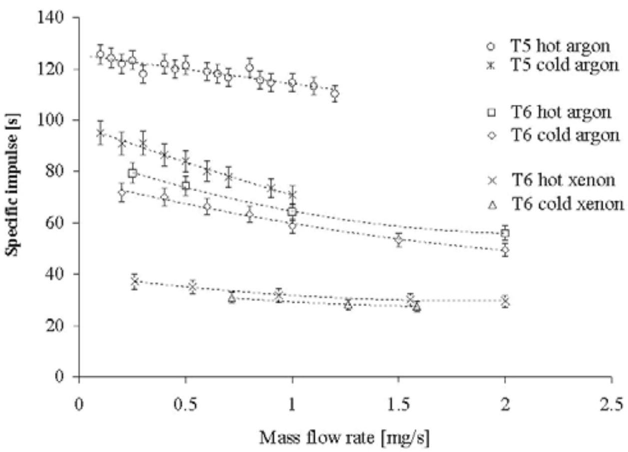

Figure 7 Specific impulse obtainable from operating the T5 (argon) and T6 cathode (argon and xenon) in a cold gas and resistojet mode (using only the heater)

The T5 thruster shows relatively high specific impulse with argon, surpassing the performance of the T6 in both modes of operation. Error bars are indicative of thrust measurement inaccuracies due to external excitations of the thrust balance, primarily from the roughing pump. Thrust measurements were made with good repeatability down to approximately 0.08mN, after which it became difficult to resolve thrust measurements with the current sensitivity of the counter-weight setup.

The smaller orifice (0.23mm) of the T5 cathode is shown to be beneficial in thrust production for the same mass flow rate, since a higher chamber pressure is maintained and thus a greater thrust produced by the adiabatic expansion from the flat plate orifice. During the heated mode, higher internal pressure also allows a greater residence time for the propellant inside the cathode, improving heat transfer from the cathode walls by conduction. This increase in heat transfer raises the chamber pressure further and thus produces a marked increase in performance over the cold gas mode, even more so when considering the respective heater powers. The T5 cathode achieved a maximum Isp of 125s at 0.12mN. This increase is much less pronounced in the T6 cathode due to the large orifice, chamber pressures therefore remain low and the resistojet mode only has a small influence on improving specific impulse. As expected operation with xenon in the T6 cathode leads to a large reduction in specific impulse due to the molecular weight of the gas, with a maximum Isp of 31.8s at 0.29mN obtained in resistojet mode. The loss of performance at higher mass flow rates is likely due to greater interaction between the expansion plume and the anode orifice edge and face. At the time of writing, T5 testing had not been conducted with xenon, however it is very likely that the T5 will also experience a reduction in performance due to the heavier molecular weight of propellant. This indicates that attainable Isp for the T5 cathode with xenon would most likely be in the 50-60s range in resistojet mode.

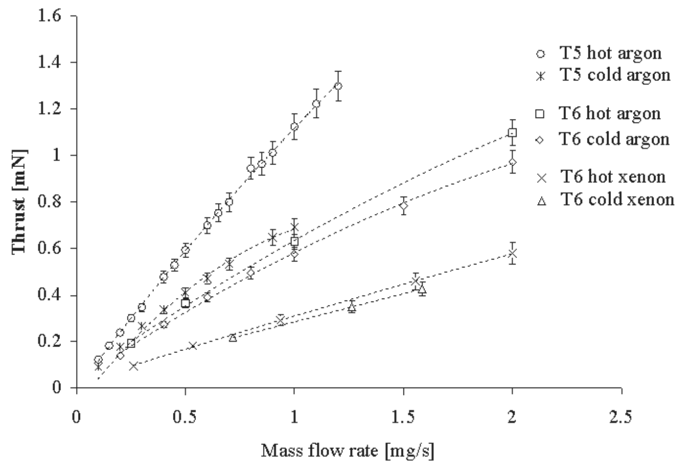

Figure 8 Thrust obtainable from operating the T5 (argon) and T6 cathode (argon and xenon) in a cold gas and resistojet mode (using only the heater)

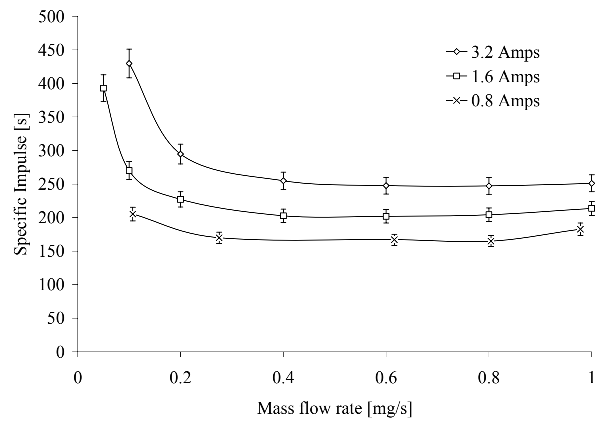

Figure 9 Specific impulse vs. mass flow rate for various throttle levels of the T5 cathode

T5 Discharge Thrust Measurement

To ensure the target was not being influenced by the plasma in which it is immersed, the target was biased +/- 30V and also directly grounded during high and low power operation. The thrust measurement system showed no sign of plasma interaction with the thrust balance affecting the thrust measurements. Results for the various current conditions for the T5 cathode are shown in Figure 9.

Results show near monotonic dependence of specific impulse on discharge current with rapidly increasing performance below 0.4mgs^{-1} for the 3.2A and 1.6A throttle settings with a less pronounced increase at 0.8A. Figure 10 and 11 shows associated thrust levels and thrust efficiencies.

Operation at low powers (<13W) in the low current condition (0.8Amp) brings relatively high specific impulse of up to 165 seconds equal to performance in a resistojet mode (and at lower power), where cathode body temperatures are in the region of 1000°C. At the high current condition operation at powers of below 30W give specific impulse in the region of 250s. Further reduction in flow rate increases operating voltage and power invested in the flow. This results in an increase in specific impulse however with declining thrust efficiency as convective and radiative losses begin to dominate.

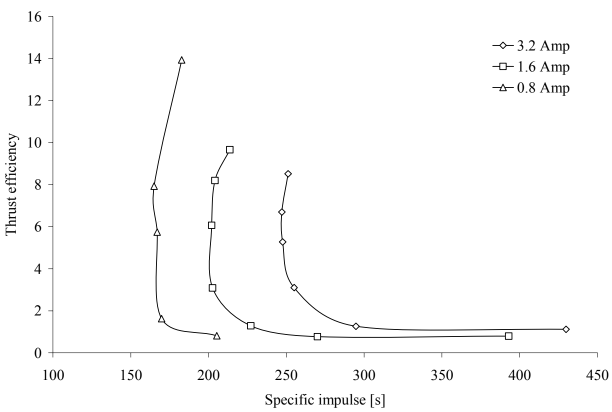

Figure 10 Associated thrust efficiencies in relation to specific impulse at various throttle conditions

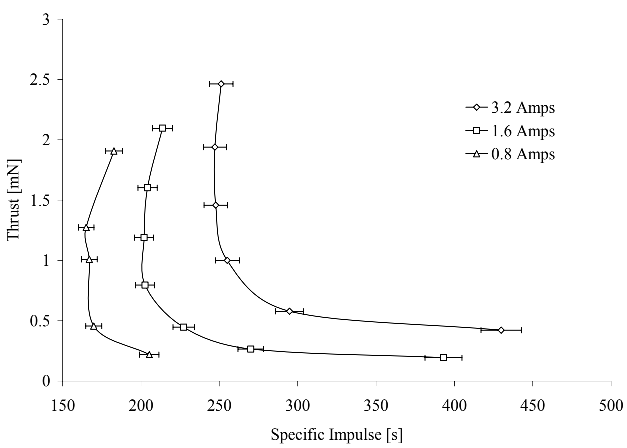

Figure 11 Thrust and specific impulse attained at various current conditions in the T5 cathode

The highest specific impulse of 429s was attained with the T5 cathode at 3.2A, with 1.1% thrust efficiency, 79W discharge power. Specific impulse can be traded for higher thrust to power ratios by increasing propellant flow rates or decreasing discharge current (however higher thrust efficiencies are obtained at higher discharge currents) generating thrust efficiencies of 14% (200μN/W) and specific impulse of 167s at 0.8Amps, and over 8% at the maximum rated current capacity of 3.2 Amps, with specific impulse ~250s (77μN/W, 35W discharge power). Up to 2.4mN could be generated at higher currents with the maximum flow rate of 1-mgs^{-1} and specific impulse over 250s.

Respective discharge powers and performance can be seen in Figure 12 and highlights the ultimate power required to generate such performance.

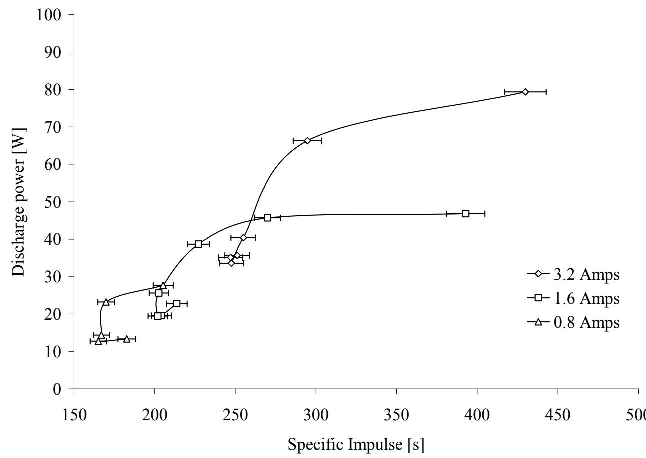

Figure 12 Performance variations with discharge power at various current conditions

T6 Discharge Thrust Measurement

Figure 13 shows that ultimately high specific impulse is dependant on discharge current since higher discharge currents are able to sustain operation at lower mass flow rates and higher powers. Operation with xenon also gives high specific is testament to the lower primary ionization energy of xenon, which enabled the cathode to operate at the lowest flow rate of 0.04mgs^{-1}. Associated thrust levels are shown in Figure 14.

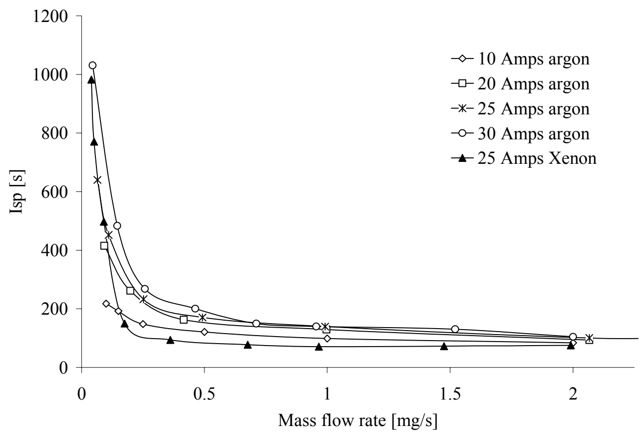

Figure 13 Specific impulse reached with the modified T6 hollow cathode at various current conditions and mass flow rates with xenon and argon

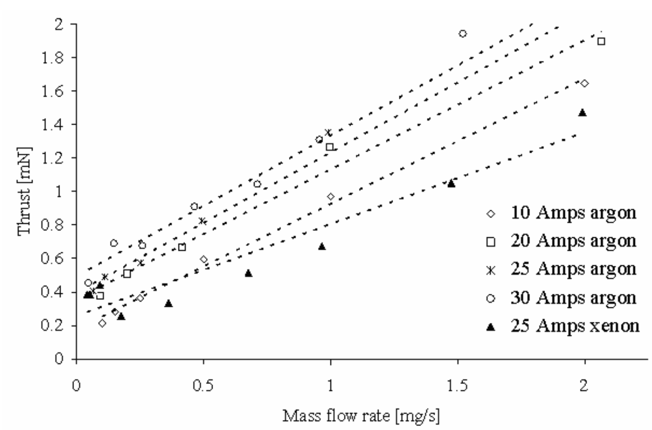

Figure 14 T6 thrust level with respect to mass flow rate at various current conditions with xenon and argon

It is clear that when extrapolating thrust level back to zero mass flow a remnant thrust production mechanism exists which is dependant on discharge current. The nature of this mechanism is discussed in more detail in [25] however indications are that it is a product of an electromagnetic blowing force which effectively constitutes a low power MPD type operation. Since large discharge currents are required to produce a relatively small blowing force, thrust to power ratios are far below 1% in all but the 30Amp case for high specific impulse. Images of the T6 cathode during operation are shown in Figure 15.

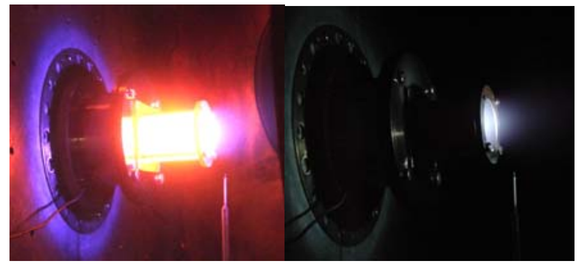

Figure 15 T6 cathode operating stably at 840W (30Amps) on argon at 0.045mgs^{-1}, 28.0V discharge voltage (left) T6 operating on xenon at 200W (25Amps) 0.5 mgs^{-1} at 8.01V discharge voltage (right)

CONCLUSION

An indirect thrust measurement technique has been developed and tested for preliminary thrust characterization of the T5 and T6 cathodes. At this time no investigation has been possible into the effect of elastic and non-elastic collisions with the target. This effect may be significant due to the planar geometry of the target. The effect is visible in operation of the cold gas thruster. The theoretical specific impulse for this type of operation should be around 50s with argon, the apparent specific impulse is around 80s. It should therefore be noted that this overestimation of thrust and thus specific impulse will also be consistent in the results for operation in a discharge mode at this preliminary stage. Future work will therefore be aimed at designing a pendulum target which is able to limit the effect of elastic collisions by controlling particle paths.

Discharge power characteristics of the T5 cathode would suggest that the application of multiple hollow cathode thrusters for all-electric spacecraft would be well within the resource constraints of larger spacecraft which also carry primary electric propulsion systems. For smaller, more resource limited spacecraft low power hollow cathode thrusters may provide a basis to complement to existing architectures or as stand-alone thrusters. T5 hollow cathode characterization has provided baseline performances for a low power plasma propulsion device. Operation at higher currents has shown to be beneficial for high thrust to power ratios and useful thrust levels. Future work should be aimed at both maintaining low discharge voltages at higher current levels and higher thrust to power ratios, and improving high end performance.

These results show that in certain operating conditions the T5 HCT is capable of impressive performance as an electro-thermal thruster with argon, explicable only by the heating of propellant up to many thousands of Kelvin (a conservative estimate based on possible overestimation of thrust), with thrust to power ratios between 30-250W/mN. The low current of the T5 suggests that the cathode likely operates as an electrothermal thruster and as such it would seem that resistive dissipation within the orifice is the specific impulse driver at any particular flow rate. Alternatively the T5 resistojet mode offers a much lower power to thrust ratio which may be beneficial for example when considering maneuvering times on initial de-spin of spacecraft on orbit insertion.

The exact thrust mechanisms of the T6 hollow cathode have been debated for some time. Our results indicate that for high specific impulse the hollow cathode operates as a low power MPD thruster. Due to the relatively low currents, electron convective and radiative losses dominate performance and thus give poor thrust efficiencies. Operation at elevated currents is likely to significantly improve performance and thrust efficiency; although this will be well beyond the rated current capacity for the T6 cathode. Thrust efficiencies are unlikely to improve significantly since this will scale quadratically with discharge current and will quickly enter much higher power regimes of operation.

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