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A centre-triggered magnesium fuelled cathodic arc thruster uses sublimation to deliver a record high specific impulse

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The cathodic arc is a high current, low voltage discharge that operates in vacuum and provides a stream of highly ionised plasma from a solid conducting cathode. The high ion velocities, together with the high ionisation fraction and the quasineutrality of the exhaust stream, make the cathodic arc an attractive plasma source for spacecraft propulsion applications. The specific impulse of the cathodic arc thruster is substantially increased when the emission of neutral species is reduced. Here, we demonstrate a reduction of neutral emission by exploiting sublimation in cathode spots and enhanced ionisation of the plasma in short, high-current pulses. This, combined with the enhanced directionality due to the efficient erosion profiles created by centre-triggering, substantially increases the specific impulse. We present experimentally measured specific impulses and jet power efficiencies for titanium and magnesium fuels. Our Mg fuelled source provides the highest reported specific impulse for a gridless ion thruster and is competitive with all flight rated ion thrusters. We present a model based on cathode sublimation and melting at the cathodic arc spot explaining the outstanding performance of the Mg fuelled source. A further significant advantage of an Mg-fuelled thruster is the abundance of Mg in asteroidal material and in space junk, providing an opportunity for utilising these resources in space. *Published by AIP Publishing.*
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The high ion velocity in the plasma produced by a cathodic arc (typically greater than 10 km/s) makes the cathodic arc a candidate for an electric propulsion system.[1–9] Pulsed, rather than steady-state, operation of the arc facilitates higher operating currents, leading to higher mean charge states and higher ion velocities.[2] Triggering the arc at the centre of the cathode improves pulse to pulse uniformity, plasma transport, and long-term reliability.[10,11] The current electric propulsion systems use compressed gases as fuel, bringing a mass burden of pressure vessels, valves, and regulators. The cathodic arc systems, like pulsed plasma thrusters,[12] utilise solid fuels, reducing the mass overhead required for fuel management. The cathodic arc thrusters eliminate two failure modes present in other electric propulsion systems, as they do not require acceleration grids, which are subject to erosion,[13] or electron guns, subject to limited lifetime, to neutralise the exhaust.[14] The operating parameters of cathodic arcs including erosion rates and ion drift velocities are dependent on the cathode material used.[3] The cathode materials chosen for this study have been selected from candidate materials identified in a prior survey of the literature.[6] A diagram of the centre-triggered pulsed cathodic arc (CT-PCA) used is shown in Fig. 1. Here, we show that the sublimation characteristics of a cathode material can be exploited to provide a higher degree of ionisation, leading to greatly enhanced specific impulses.

The fuel specific impulse of a propulsion system is a measure of the efficiency of reaction mass in generating thrust.[12] The fuel specific impulse, I_{sp}, is defined as

$$I_{sp} = \frac{T}{\dot{m}g} = \frac{v_e}{g}, \quad (1)$$

where T is the thrust, $\dot{m}$ is the exhaust mass flow rate, v_e is the velocity of the exhaust relative to the rocket, and g is the acceleration due to gravity at sea-level. Jet power efficiency (JPE) is the ratio of the kinetic power carried by the exhaust flow to the electrical power consumed by the system in generating the flow and is defined as

$$JPE = \frac{\frac{T^2}{2\dot{m}}}{\frac{\int V(t)I(t)dt}{\Delta t}}, \quad (2)$$

where $V(t)$ is the instantaneous cathode voltage at time t voltage and $I(t)$ is the instantaneous cathode current. The integration is carried out over a pulse of duration Δt. The jet power efficiency is often expressed as a percentage. The existing

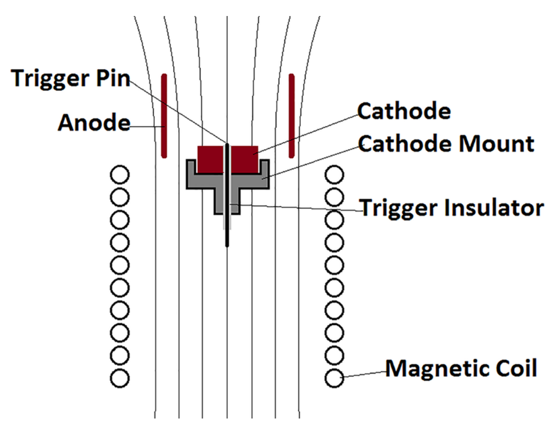

FIG. 1. Diagram of the experimental setup, with the configuration of the imposed magnetic field that forms the magnetic nozzle.

"flight rated" Hall Effect and gridded ion thrusters have demonstrated specific impulses in the range of 2500–4000 s.[14] Laboratory tests on NASA's experimental HiPEP gridded ion thruster gave a maximum specific impulse of 9600 s.[13] The jet power efficiency of various electrical propulsion systems range from 55% to 80%, with HiPEP performance being towards the upper end of that range.[13,14] The determination of these two metrics for pulsed arc thrusters requires the experimental measurement of thrust and cathode mass erosion rate; this letter summarises work done to determine these metrics for a number of candidate materials used as fuel. We explore the possibility that the centre-triggered pulsed cathodic arc thrusters can exceed the current performance records of systems that have been tested for flight applications.

Our previous study[6] found that the candidate cathode materials for PCA thruster fuels fell into easily identifiable categories, two of which were refractory metals (e.g., Ti, Mo, W, and Ta) and light elements (e.g., Mg and C). The previous predictions of impulse were based on a diverse set of measurements reported in the literature, made under a wide range of experimental conditions and thus were only indicative. Here, we obtain the erosion rate and thrust measurements for the selected elements under identical experimental conditions and used them to derive both the fuel specific impulse and the jet power efficiency. The aim of this letter is to compare, as representatives of the two categories mentioned above, titanium- and magnesium-fuelled CT-PCA thrusters. Titanium was selected for this comparison as it has been studied previously as a fuel for PCA thrusters[7] while Mg was selected because it showed the highest efficiencies of all the elements we tested.

Thrust measurements were made using a ballistic pendulum,[4] constructed from polymers, such as cellulose acetate, known to have high metallic ion condensation and implantation coefficients.[22–24] The deflection of the pendulum was recorded as a function of time using the optical method described in the supplementary material. The conversion of the deflection of a ballistic pendulum into a thrust is reliable, provided that allowances are made for the limited capture cross section and the effects on the momentum imparted to the pendulum by an incident ion rebounding or causing sputtering. Sticking coefficient data for metal ions on like metals[25] and on different metals[26] were taken from the literature. A survey of the results indicates that a sticking coefficient of 0.8 is appropriate for the materials investigated here. In this case, the remaining 20% of the impacting ions rebound and thus contribute extra momentum to the pendulum. In our analysis, we assume that these rebounding ions collide elastically, imparting twice their initial momentum to the pendulum, which leads to the pendulum momentum being 1.2 times the plasma momentum. We multiply the measured pendulum impulse by the inverse of this factor (0.833) to account for this. A further correction was made to account for the sputtered atoms that also impart some additional momentum to the pendulum, using published data on sputter yields[27,28] as described in the supplementary material.

Erosion rates were measured by weighing the cathode before and after a known number of pulses were fired.[5] The 25 mm diameter cathodes of 99%+ purity were sourced from the Kurt J Lesker Company. The parameters explored were pulse length and capacitor bank charging voltage, the latter determining the discharge current. The measurements were taken at pulse lengths ranging from 100 to 300 μs and charging voltages (V_{ch}) ranging from 100 to 180 V (corresponding to average currents ranging from 1.5 to 4 kA). Data were captured in Tektronix TDS 2400 series digital storage oscilloscopes and processed to calculate the fuel specific impulse and the jet power efficiency values plotted in Fig. 2. All I_{sp} data points have 15% uncertainty, while all JPE data points have 20% uncertainty (see the supplementary material).

Figure 2(a) shows that the fuel specific impulse of Ti-fuelled CT-PCA thrusters increases with energy expended per pulse at a constant pulse duration, but decreases with pulse duration at a constant energy expended. The Ti jet power efficiencies shown in Figure 2(b) show that short, high current pulses are most efficient, as expected from reports on high current arcs in the literature. High current arcs produce higher

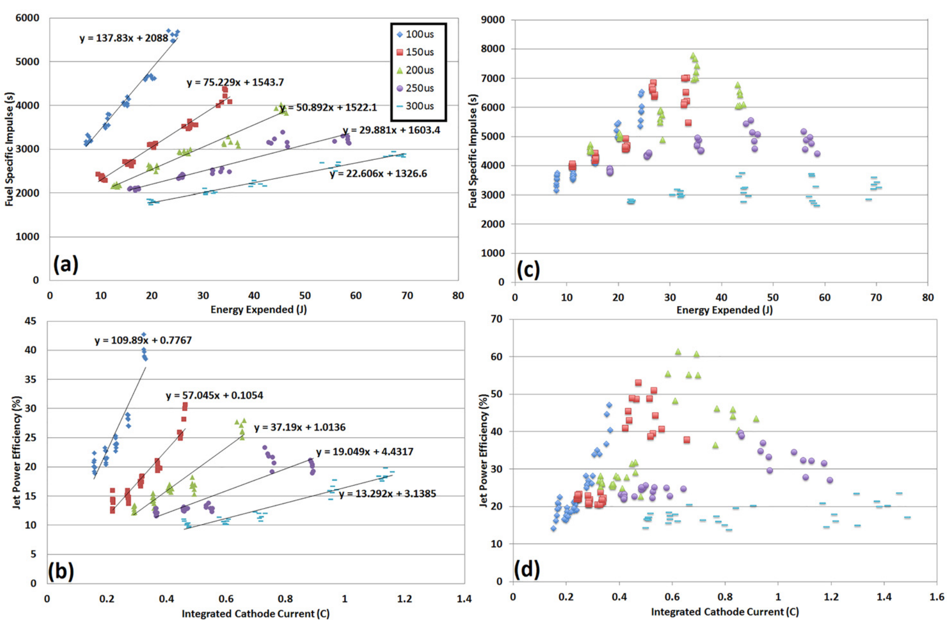

FIG. 2. Plots of fuel specific impulse as a function of energy expended in the plasma per pulse ((a) and (c)) and jet power efficiency (JEP) as a function of integrated cathode current per pulse ((b) and (d)). Plots (a) and (b) show Ti data, plots (c) and (d) show Mg data, and the legend shows the pulse durations used. All trendlines shown are linear fits with $r > 0.95$. Energy expended is defined as per the integral in Equation (2), while integrated cathode current is the integral of cathode current over the duration the pulse.

ion charge states.[29] The production of more neutral species as the pulse progresses leads to a reduction of ion energies, mean ion charge state, and ionisation fraction due to ion collisions with the neutral species as the pulse progresses.[15–21] The Mg data in Fig. 2(c) show a clear optimal configuration, where the specific impulse peaks at the 160 V_{ch} pulses of 200 μs duration, and a peak for the same parameters is seen in the Mg jet power efficiency in Fig. 2(d). The decline after the peak is due to side-arcing; once the arc is triggered, plasma is expelled from fast moving generation sites on the face of the cathode termed cathode spots. The cathode spots repel each other, and in the case of centre-triggered systems, the spots will move to the edge of the cathode and begin arcing directly to the anode from the sides.[10] Side-arcing erodes material from the sides of the cathode without producing thrust, thus reducing efficiency. Higher currents produce more cathode spots, and their mutual repulsion leads to higher spot velocities, which in turn leads to an earlier transition to side-arcing.[11,18] The Mg experiments performed without the solenoid coil in place show a typical reduction in performance due to side arcing between 35 and 45 J pulses. This explains the transition to flatter curves in the Mg data for longer pulse lengths.

To explore the effect of magnetic field focusing, a solenoid coil of 10 turns with internal diameter of 100 mm and length of 80 mm with the magnetic field shaped to act like the expansion bell of a rocket nozzle was placed as shown in Figure 1. The current intercepted by the anode flows through the coil with average currents in the range of 150–550 A, producing the mid-solenoid magnetic fields of 30–110 mT. The typical voltage and current traces are shown in the supplementary material. The pendulum location was changed after installation of the magnetic nozzle due to chamber geometry limitations and the need to fit the coil between the cathode and pendulum. The measured values were adjusted to account for an increased distance to the pendulum to accommodate the coil and the magnetic plasma focusing effects of the coil. For details of the calculation of these adjustments, see the supplementary material.

The magnetic nozzle greatly increases the performance measured on both metrics. The jet power efficiency and the fuel specific impulse results with the magnetic nozzle installed are plotted as a function of expended energy per pulse in Figure 3 for both the Mg and Ti cathodes. All the data plotted are for 200 μs pulse length as this was found to be the optimum pulse length for Mg without the magnetic nozzle. Data from experiments performed without a magnetic nozzle are also plotted for comparison. The results show that the fuel specific impulse exceeds the performance band of NASA HiPEP (indicated by the purple rectangle) for Mg pulses where energy supplied is over 30 J per pulse.[13]

An operational advantage of the magnetic field is that it inhibits the transition to side-arcing. The reduction in performance associated with side-arcing is not observed with the magnetic coil in place for 200 μs pulses. Applying the external magnetic field to the cathode surface steered the cathode spots via the retrograde $\mathbf{J} \times \mathbf{B}$ effect,[1] leading to longer cathode spot trajectories and therefore longer pulses before side-arcing is observed. No side arcing was observed in pulses on Mg up to a charging voltage V_{ch} of 180 V (with peak current ~2.3 kA and pulse length 200 μs). Side arcing was observed

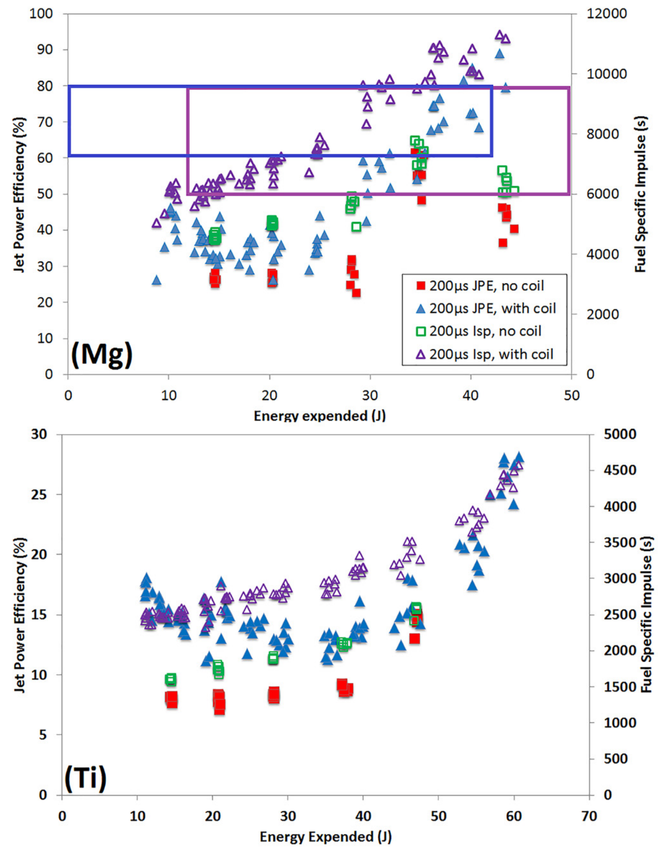

FIG. 3. Mg (top) and Ti (bottom) efficiency metrics with and without the magnetic nozzle; solid symbols denote Jet Power Efficiency (JPE) on the left axes, while hollow symbols denote Fuel Specific Impulse (I_{sp}) on the right axes. Triangles show results for experiments done with the magnetic nozzle whilst squares show those for experiments carried out in the absence of the nozzle. HiPEP performance bands are shown as rectangles, the purple for I_{sp} and the blue for JPE, extending from the relevant axes into the Mg performance envelope. All plasma pulses were 200 μs in duration.

only in Ti pulses of greater than a V_{ch} of 250 V (with a peak current of ~2.6 kA and a pulse length of 200 μs). The enhancement of performance by the magnetic nozzle is attributed to the end-Hall effect, previously used in ion sources,[33] in which the positive ions are accelerated by the plasma potential gradient as they move into a region of decreasing magnetic field strength.

The improved performance of Mg over Ti as a cathode material is likely a result of the lower erosion rate of Mg. We propose that the high sublimation vapour pressure of Mg, leading to sublimation as the primary erosion mechanism, is the reason for its exceptional performance (measured erosion rates shown in the supplementary material). Figure 4 shows a schematic diagram comparing the erosion characteristics of a cathodic arc erosion crater in a material

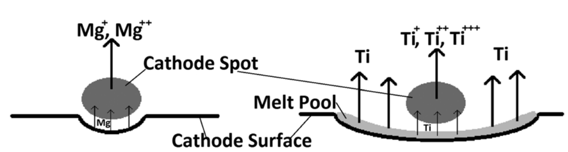

FIG. 4. Illustration of the difference in erosion between a subliming cathode spot (left, for Mg) and a cathode spot in which cathode melting occurs (right, for Ti).

that sublimes with one that melts. When melting occurs, the melt pool is likely to extend well beyond the ionisation zone of the cathode spot plasma because of the low viscosity of the liquid. In the case of Ti (melting point 1941 K; vapour pressure of 1 Pa at 1982 K,$_{30}$ vapour pressure at melting 0.53 Pa (Ref. 31)), the creation of a surface melt pool results in the formation of macroparticles as well as neutral vapour.[2] In contrast to the case of Mg (melting point 923 K; vapour pressure of 1 Pa at 701 K,[30] vapour pressure at melting 330 Pa (Ref. 31)), its high sublimation vapour pressure prevents the formation of a melt pool. Sublimation liberates material from the cathode directly into the ionisation zone of the cathode spot.[32] Since macroparticle and neutral emission results in mass flux without appreciable momentum transfer (macroparticles have approximately thermal velocity[2]), the macroparticles generated by Ti lowers its efficiency.[34–37]

The results from these experiments show that the Mg fuelled CT-PCA thruster generates thrust with specific impulse of up to 11 360 s, superior to competing electric propulsion systems. Flight-rated Hall Effect and gridded ion thrusters have specific impulses in the range of 2500–4500 s, and reported laboratory tests of NASA HiPEP show specific impulses as high as 9600 s.[13,14] The jet power efficiency of the Mg fuelled CT-PCA is competitive with other electrical propulsion systems that show values in the range of 55%–80%.[12,14]

Comparison of our results with those of the edge-triggered systems of Keidar, Schein, Polk, and others shows the benefits of centre triggering. The edge-triggered PCA thrusters have specific impulses of approximately 3000 s and jet power efficiencies of approximately 15% when using Ti as the fuel, with a magnetic nozzle.[7–9] When using Ti fuel with pulses of 200 μs, the centre-triggered system used in this work gave a specific impulse of 2500 s and a JPE of 15% without the magnetic nozzle. Adding the magnetic nozzle significantly increased system performance to give a specific impulse of 4600 s and a JPE of 28%.

In this work, we have demonstrated the concept of a CT-PCA thruster, and have shown that its performance on two metrics exceeds those of competing electric propulsion systems. We find that the confluence of the choice of magnesium as a fuel, high current operation, and centre triggering are keys to the exceptional performance. The demonstrated specific impulses are high enough to enable a spacecraft to move from low earth orbit to destinations in the inner solar system, such as a Mars orbit and return without the need for refuelling. The abundance of Mg in asteroidal material and space junk provides the opportunity to refuel in space, eliminating the substantial costs involved in transporting fuels from Earth.

See supplementary material for detailed descriptions of the ballistic pendulum, uncertainties, and measurement adjustments due to chamber geometry and magnetic focussing as well as cathode erosion rates.

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