EFFECT OF A PULSED MAGNETIC FIELD ON ARCJET OPERATION

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Abstract

This study evaluates the effects of a moderate strength (1 Tesla), highly divergent axisymmetric pulsed magnetic field on the operation of a 1 kW arcjet. The pulsed magnetic field is produced by an overdamped LC circuit with peak current at 9 ms. The effect of the varying magnetic field on the arcjet operating voltage is monitored for propellant flow rates of 40, 50, and 55 mg/s. The magnetic field increases arcjet operating voltage, $\Delta V_{arc}$, by up to 6 volts, with negligible effect on thruster current. For slowly varying fields, $\Delta V_{arc}$ varies linearly with field strength and coil current, suggesting a plasma swirl effect. As propellant flow rate decreases, $\Delta V_{arc}$ increases at constant magnetic field. Thermal tests show that $\Delta V_{arc}$ is independent of arcjet operating temperature. No unwanted voltage oscillations are observed to be induced by the applied magnetic field on the arcjet voltage waveform. The pulsed magnetic field is observed to have a noticeable effect on the thruster plume.

Nomenclature

\begin{itemize}
  \item $a$: Mean radius of coil [cm]
  \item $b$: Axial length of coil [cm]
  \item $B$: Magnetic field [T]
  \item $c$: Radial width of coil [cm]
  \item $C$: Capacitance of RLC circuit [F]
  \item $I_{max}$: Maximum coil current [A]
  \item $I_{coil}$: Coil current [A]
  \item $I_{arc}$: Arcjet current [A]
  \item $L_1$, $L_2$: Coil 1 and 2 self-inductance [$\mu$H]
  \item $L$: RLC circuit inductance [$\mu$H]
  \item $N_1$, $N_2$: Number of turns in coil
  \item $R$: RLC circuit resistance [$\Omega$]
  \item $t_{max}$: Time of maximum current [s]
  \item $\tau$: Skin depth characteristic time [s]
  \item $V_o$: Capacitor charging voltage [V]
  \item $V_{coil}$: Coil voltage [V]
  \item $\Delta V_{arc}$: Change in arcjet operating voltage [V]
  \item $V_{max}$: Coil voltage at $t_{max}$ [V]
  \item $\Delta z$: Distance between coil centers [cm]
  \item $\delta$: Skin depth [cm]
  \item $\kappa_e$: Electron thermal conductivity [W/m-K]
  \item $\mu_0$: Vacuum permeability [H/m]
  \item $\sigma_c$: Electrical conductivity [W-m]$^{-1}$
  \item $\omega$: Frequency [sec$^{-1}$]
  \item $\Omega_e$: Electron Hall parameter
\end{itemize}

I. Introduction

Arcjet propulsion systems offer significant propellant mass savings for missions ranging from north-south station-keeping to orbit maneuvering to orbit transfer. The propellant savings can then be used to reduce launch mass, increase payload, and/or increase satellite lifetime. The electrothermal arcjet thruster was initially studied both theoretically and experimentally in the 1950's, and low power arcjets were first tested in the 1960's for station-keeping missions. The increased need for higher specific impulse on geosynchronous satellites has renewed interest in arcjet technology, particularly the hydrazine arcjet, as a station-keeping propulsion system, with first commercial application scheduled for 1993. However, improvements in thruster efficiency and performance are still desired to accomplish various missions.

Several factors limit arcjet performance, including thermal losses to the anode, wall

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friction losses in the nozzle, and frozen flow losses in the nozzle expansion process. The application of a relatively strong magnetic field to an arcjet may have several effects, including decreased thermal losses to the nozzle wall and increased particle residence time, plus a spatial redistribution of ohmic heating, particularly in the constrictor.

The addition of an applied magnetic field to an arcjet, with components $B_r$ and $B_z$, will result in a complex interaction with the plasma. One of our goals is to use a pulsed magnetic field as a diagnostic and eventually to understand the interactions with the help of an applied field arcjet code.

Previous research by Andrenucci et al. has shown that an externally applied magnetic field (up to 0.12 T) increases thruster voltage and confines the exhaust plume. Analysis of magnetic nozzle flow in a pulsed MPD thruster has shown that the applied field aids in increasing the thrust at constant discharge current. Magnetic nozzles have been shown to lead to higher velocities and temperatures than a corresponding adiabatic flow.

With an applied field the electron Hall parameter $\Omega_e$ in the arcjet constrictor is increased. Since the electron thermal conductivity $\kappa_e$ scales as $\Omega_e/(1+\Omega_e^2)$, $\kappa_e$ decreases for an applied field arcjet. This translates into a decreased thermal load on the constrictor wall. The applied field introduces an azimuthal Lorentz force which increases propellant swirl, improving heat exchange between the cold injected propellant and the discharge and preventing localized anode attachment of the discharge, thus extending electrode lifetime.

II. Apparatus

The objective of this investigation is to understand the effects of a strong, highly divergent magnetic field on the operating characteristics of a 1 kW arcjet. The highly divergent magnetic field enables the arc discharge to attach to the nozzle wall and not protrude out the exit to reattach to the downstream surface of the anode. The arcjet used is a 1 kW hydrazine design from NASA Lewis, with tangential (swirl) injection of the propellant.

Magnetic Coil Design

In order to generate a 1 T magnetic field with high divergence angle, a cusp field design is used, created by two coils of different size with equal but opposite currents. The coil current is pulsed by a 1 kJ capacitor bank to prevent excessive coil heating, and the pulse width is significantly larger than the anode skin depth time $\tau$ to allow time for the field to build up in the plasma.

The characteristic skin depth time is calculated for the molybdenum tungsten anode structure from:

$$\tau = \pi \mu_0 \sigma_c \delta^2$$

where $\delta$ is taken as the anode radius, 1.6 cm. In Eq. (1) $\sigma_c$ is the electrical conductivity of the anode and is taken as $(\sigma_c)_{\text{moly}} = 4.1 \times 10^6 \text{[cm}/\text{m}]^{-1}$ at 1173 K. A conservative calculation of $\tau$ uses the conductivity of molybdenum since it is larger than that of tungsten.

RLC Circuit

The field coil is driven by three 10,000 µF electrolytic capacitors, which with the coil inductance $L$ and resistance $R$, form an RLC circuit. The damping factor for the RLC circuit is $CR^2/4L = 2.5$. The time to reach maximum current, $t_{\text{max}}$ is:

$$t_{\text{max}} = \frac{1}{\omega} \tanh \left( \frac{2L\omega}{R} \right)$$

where $\omega$ is:

$$\omega = \left( \frac{R^2 - \frac{1}{4L^2}}{LC} \right)^{1/2}$$

Magnetic Field Calculations

The resulting high divergence magnetic field is shown in Fig. 1. To calculate the magnetic field pattern the radial and axial components of $B$ are required. The two coil design is approached by first calculating the magnetic field produced by a single loop at all points $(r,z)$. An estimate of $B$ is then obtained by multiplying by the number of turns in each coil, and adding $r$ and $z$ vector components.

To meet the design constraints a spreadsheet was used to calculate the required capacitance, maximum current, coil voltage ($V_{\text{max}}$) at $t_{\text{max}}$ and magnet wire diameter required to attain
The magnetic coil satisfying the design constraints is shown in Table 1:

<table>
<thead>
<tr>
<th>RLC Circuit</th>
<th>COIL 1</th>
<th>COIL 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vmax: 250 V</td>
<td>N1: 290 turns</td>
<td>N2: 145 turns</td>
</tr>
<tr>
<td>L1: 4163 uH</td>
<td>a1: 3.05 cm</td>
<td>a2: 3.05 cm</td>
</tr>
<tr>
<td>L2: 1170 uH</td>
<td>b1: 2.5 cm</td>
<td>b2: 1.43 cm</td>
</tr>
<tr>
<td>Imax: ±187 A</td>
<td>c1: 2.0 cm</td>
<td>c2: 2.0 cm</td>
</tr>
<tr>
<td>Vmax: 207 V</td>
<td>Mag. Wire: 16 AWG</td>
<td>Mag. Wire: 16 AWG</td>
</tr>
<tr>
<td>tmax: 9.3 msec</td>
<td>Imax1: 187 A</td>
<td>Imax2: -187 A</td>
</tr>
<tr>
<td>C: 30,000 μF</td>
<td>Energy in 2 coils: 938 I</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Magnetic coil specifications. Coil 1 has 290 turns with a peak of +187 A, and coil 2 has 145 turns, with a peak of -187 A. The two opposing coils form a magnetic cusp. Axial coil separation is Δz = 3.1 cm.

The coil is cooled by two copper cooling tubes, at locations 1 and 2 (Fig. 2), attached to the bobbin with copper based epoxy. Based on an approximate heat transfer calculation, a water mass flow rate of 1 g/sec is required for a 20 °C rise. A flow of 20 g/sec of H2O was used in this experiment.

Due to the spread of the thruster exhaust plume, a 45 degree chamfer is machined in the bobbin inner diameter to prevent plume interference (Fig. 2). The coil is mounted concentrically to the arcjet.

III. Diagnostics

In order to observe the effects of the applied magnetic field on arcjet operation, time-dependent thruster and coil voltage-current measurements are performed. Table 2 describes the diagnostics for these measurements.

The coil voltage is obtained with a 50 Ω BNC cable fed into a 10x BNC attenuator on the face of a Soltec 10 MHz digital oscilloscope.

Thruster voltage is measured with a 10x voltage probe, attached to the cathode lead after arcjet ignition. This prevents the 4000 volt start-up circuit from damaging the oscilloscope.

Table 2. Experimental diagnostics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Max. Value</th>
<th>Diagnostic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil Voltage</td>
<td>250 Volts</td>
<td>50Ω, 10x atten, Soltec scope</td>
</tr>
<tr>
<td>Coil Current</td>
<td>200 Amps</td>
<td>20 mΩ resistor</td>
</tr>
<tr>
<td>Thruster Voltage</td>
<td>120 Volts</td>
<td>10x Vprobe</td>
</tr>
<tr>
<td>Thruster Current</td>
<td>10 Amps</td>
<td>20 mΩ resistor</td>
</tr>
<tr>
<td>m</td>
<td>55 mg/s</td>
<td>UNIT Flow Controllers</td>
</tr>
</tbody>
</table>

The propellant mass flow rate is monitored by two Unit Instruments mass flow controllers: one for hydrogen and the other for nitrogen. The two gases are mixed downstream of the controllers to form simulated hydrazine.

The magnetic field generated by the coils can be found by measuring the induced voltage in a search coil. The time-dependent magnetic field is then obtained by time-integrating the induced voltage. This technique is currently being implemented in order to quantify the skin depth effect of the anode on the field in the plasma region.

IV. Experimental Procedure

The arcjet is located inside the coil as shown in Fig. 2. At the constrictor the magnetic field is typically +0.5 Tesla and near the exit the field is -0.1 Tesla. Between the constrictor and the exit plane the Bz field falls to zero and reverses (Fig. 3). The Bz=0 location is 9.4 mm downstream from the constrictor. Near the exit plane, coil 2 causes the field to intersect the nozzle wall at a large angle. At the constrictor the magnetic field is large and is predominately axial.

The arcjet/coil assembly is mounted in a five-way cross coupled to a 1.5 m³ vacuum tank. A 4500 CFM (2125 l/s) pumping system provides a background pressure of 0.05 Torr at a nominal mass flow rate of simulated hydrazine of 50 mg/s. During operation the arcjet voltage is typically 110 V at 10 A. Experiments are started
after a 3-5 minute arcjet warm-up period. The thruster current level is set at 10 A, and experiments are performed at mass flow rates of 40, 50, and 55 mg/s. The charging voltage of the capacitor bank driving the field coils is varied between 25<Vo<100 volts, producing a maximum B of 0.06<B<0.24 Tesla at the constrictor. Visual observations of the plume characteristics are also made during the experiment.

**Pulsed Coil Operation**

The theoretical current waveform for an overdamped RLC circuit representing the pulsed magnet is shown in Fig. 4. Experimental current waveform data is also shown.

The variation of arcjet voltage during a pulse is shown in Fig. 5, taken for conditions of 50 mg/s hydrazine at I=10 A, and Vo=100 V. High frequency oscillations are not observed on the voltage waveform up to the 1.25 MHz data sampling rate of the oscilloscope.

**Thermal Tests**

An experiment was conducted in which ΔV<sub>arc</sub> was measured during the arcjet warm-up period. For 55 mg/s, I<sub>arc</sub> = 10 A and Vo=50 volts, ΔV<sub>arc</sub> was measured at time intervals of 3, 6, 9, and 12 minutes from start-up. No change in ΔV<sub>arc</sub> was observed during these tests.

**Coil Current Tests**

The capacitor charging voltage V<sub>0</sub> was varied, with the propellant flow rate and I<sub>arc</sub> held fixed. Figure 6 shows the increase in maximum ΔV<sub>arc</sub> with V<sub>0</sub> at several flow rates. At V<sub>0</sub> ≤ 25 volts, no change in V<sub>arc</sub> could be measured. The change in arcjet operating voltage is observed to depend on mass flow rate, with higher ΔV<sub>arc</sub> at low m.

**Plume Characteristics**

Qualitative observations were made of the effects of the pulsed magnetic field on the arcjet plume. During application of the pulsed magnetic field, the plume near the arcjet exit appears to expand outward; as the field decays in strength, this expansion recedes back into the nozzle.

**VI. Discussion and Conclusions**

Several reasons may be postulated for the observed increase in arc voltage with magnetic field. The field has a confining effect on the current in the constrictor, which would tend to increase the current density and voltage drop in this region. The reduction in κe in the constrictor noted earlier would have the opposite effect, as reduced κe would increase Te and reduce the plasma resistivity.

A plot of ΔV<sub>arc</sub> vs. coil current (Fig. 7) suggests that the increase in ΔV<sub>arc</sub> may be a plasma swirl effect, as ΔV<sub>arc</sub> is observed to be linear with I<sub>coil</sub>. In the nozzle, plasma swirl would introduce u<sub>0</sub>B<sub>Z</sub> and u<sub>0</sub>B<sub>r</sub> induced electric field components, linear with B if u<sub>0</sub> is constant. Reversing the coil current and B would help to resolve this question, if ΔV<sub>arc</sub> were also observed to change sign.

It was found that the pulsed field increase of arcjet operating voltage, produces a larger effect at lower flow rates. The observed linearity of ΔV<sub>arc</sub> with B suggests a swirl-related effect. Increased ΔV<sub>arc</sub> at reduced flow rates would occur if u<sub>0</sub> were to increase at low m. It is our opinion that a numerical model is probably required to unravel the effects of the applied field.

No significant oscillations on the arcjet voltage signal were introduced by the pulsed magnet. This may be related to the high divergence of the field, which provides conduction electrons an unimped path to the anode wall.

**VII. Acknowledgments**

The authors would like to acknowledge the Department of Aeronautical and Astronautical Engineering at the University of Illinois for financial support; graduate students S. Bufton, R. Foeilsche, T. Megli, J. Otto, and G. Willmes for help in the laboratory; and R. Hendricks, and J. Frizell for their aid in building the experiment.

**VI. References**


Fig. 1 Magnetic field patterns inside the constrictor region of the 1kW arcjet.

Fig. 2 Schematic of the coil/arcjet configuration. The arcjet is situated inside the coil so that a 1 T highly divergent field is created in the constrictor region. Water cooling is located at points 1 and 2, close to the anode.

Fig. 3 Plot of the axial magnetic field at r=0 as a function of the axial distance along the thruster axis. $B_z=0$ point lies approximately 2mm upstream of the exit plane for these experiments. The field in the constrictor is about 45% of maximum.
Fig. 4 Comparison of experimental and theoretical waveforms of coil current for $V_0=100$ Volts.

Fig. 5 The change in arcjet operating voltage due to the pulsed magnetic field vs. time, for $V_0=100$ V. Conditions are $I_{arc}=10$ A and a flow rate of 50 mg/s. Peak $\Delta V_{arc}$ is reached near the time of peak coil current and B field.

Fig. 6 The change in arcjet operating voltage as a function of charging voltage ($V_0 \sim B$) for three different propellant flow rates; $I_{arc}=10$ Amps.

Fig. 7 $\Delta V_{arc}$ versus coil current in the tail of the pulse, for 50 mg/s, $I_{arc}=10$ A and $V_0=100$ V. 40 A coil current corresponds to roughly 0.24 Tesla peak field in the constrictor. The $\Delta V_{arc}$ is linear in coil current over this range.