Numerical analysis tool for design and optimization of a coaxial pulsed plasma thruster

Carlos A. Vitulich#1, Andrés M. Cimino#2

# Centro de Investigaciones Aplicadas – DGID – Fuerza Aérea Argentina
Av. Fuerza Aérea 6500 – Córdoba – Argentina

1 carlosalbertovitulich@gmail.com
2 andres.cimino@gmail.com
Background

MICROSATELLITE µSAT-3

ABLATIVE PULSE PLASMA THRUSTER

Mision
- Station keeping
- Attitude control
- Precision photo shoot aiming.
Ablative pulse plasma thruster concept

In a PPT, a layer of a solid propellant surface –PTFE – is ablated due to the action of a pulsing electric arc applied nearby. The ablated material is then accelerated, not only by a thermal expansion but also by Lorenz forces generated by self consistent electric and magnetic fields.
Objectives

**Mathematical model and simulation**
- To develop a tool to be able to simulate a PPT behavior.
- Performance analysis to find the optimal PPT configuration.
- To verify the obtained configuration by means of numerical optimization

**Performances**
The main objective is to achieve the following requirements
- Total impulse = 1500Ns.
- Bit impulse ≈ 200 μNs.
- Power ≤ 25W.
- Maximal number of discharges ≤ 10^7.
INTRODUCTION

Development model P4S-1

Vacuum chamber tests. Experimental data.

Pre-qualification mode P4S-1

Components manufacturing and engineering model integration

Physical problem modelization, geometry validation, simulation and optimization

New design is proposed

New concept, two thruster units

Mechanical design based on simulation result data
PHYSICAL MODEL

Ablation mechanisms

A tiny layer-shaped portion of propellant is heated and removed due to the action of a quick energy pulse. The utilization of low thermal conductivity polymeric propellant allows a fast temperature increase on the exposed surface, a phenomenon which produces a violent propellant vaporization.

Model assumptions

• The conservation laws of the system are used in integral form for a Control volume.
• The control volume is defined by the acceleration channel.
• The plasma’s electrical resistance depends on the current’s normal area.
• Ionization: quasi-neutrality condition (Saha’s Eq.)
• Gas-dynamic expansion is neglected.
• Ablation heat is only transmitted by conduction.
• Debye sheath effect is neglected.
• Material properties such as thermo-ionic emission are not considered in this model.
PHYSICAL MODEL

Model equations

**Electrical charge conservation**

\[ \frac{dQ}{dt} = -I \]

**Circuits equation (Currents time variation)**

\[ \frac{dI}{dt} = \frac{1}{(L_c + \lambda l^*)} \left[ \frac{Q}{C} - \lambda \bar{u}I - \bar{R}T I \right] \]

**Ablation model**

\[ \frac{dm_A}{dt} = \frac{kA_A}{H_A} (T - T_A) \Delta x_{\text{cond}} \]

**Plasma layer movement**

\[ \frac{dl^*}{dt} = \bar{u} \]

**Total impulse variation**

\[ \frac{dI_T}{dt} = \frac{1}{2} \lambda I^2 + \bar{P}A^* \]

**Mass variation in the control volume**

\[ \frac{dm_v}{dt} = \frac{kA_A}{H_A} \frac{(T - T_A)}{\Delta x_{\text{cond}}} - \frac{1}{2\bar{u}} \lambda I^2 - c_B \bar{P}A^* \]

**Momentum conservation**

\[ \frac{m \, d\bar{u}}{dt} = \frac{1}{2} \lambda I^2 - \bar{P}A^* \]

**Energy conservation**

\[ m_{c_v} \frac{d\bar{T}}{dt} = \bar{R}(\bar{T})I^2 - \left( \varepsilon_r A_r \sigma \bar{T}^4 + kA_A \frac{(T - T_A)}{\Delta x_{\text{cond}}} \right) + m_A c_v \bar{T}_A - m_s c_v \bar{T} \]

**Ionization model (Saha)**

\[ n_e n_p = \frac{(2\pi m_e k_B T)^{3/2}}{\Delta x_{\text{cond}}} e^{-\frac{I_p}{k_B T}} \]

**PPT electric efficiency**

\[ \eta_P = \frac{P_{\text{plasma}}}{P_{\text{Cap.bench}}} = \frac{I_{\text{bit}}^2}{2mE_{\text{Cap.bench}}} \]
CODE STRUCTURE

Data input
✓ **Geometrical parameters:**
  • Cathode radius
  • Anode radius
  • Acceleration channel length
  • PTFE propellant bar length
✓ **Electrical parameters:**
  • Voltage CB
  • Capacity CB

Simulation

Data output
• Bit impulse
• Specific impulse
• Ablated mass
• Energetic efficiency $\eta$
• Number of discharges
• Required PTFE bar length
CODE VALIDATION

Calibration results

Experimental results
• Bit-impulse.
• Ablated mass.
• Frequency, period and amplitude of the tension response pulse in time.

Setting variables
• Radiant surface
• Initial thermal conductivity delta

Model and code limitations
• Zero dimensional (integral) model
• Requires adjustment values
• Not validated for thrusters with different geometries or performances
• Should be used with similar configurations

<table>
<thead>
<tr>
<th>Primer pico</th>
<th>2250V</th>
<th>2500V</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primer valle</td>
<td>-1750V</td>
<td>-3600V</td>
<td>&gt; 100%</td>
</tr>
<tr>
<td>Segundo pico</td>
<td>1100V</td>
<td>900V</td>
<td>18%</td>
</tr>
<tr>
<td>Segundo valle</td>
<td>-900V</td>
<td>-1500V</td>
<td>67%</td>
</tr>
<tr>
<td>Período promedio</td>
<td>3.9µs</td>
<td>4µs</td>
<td>2.5%</td>
</tr>
<tr>
<td>t de establecimiento</td>
<td>20µs</td>
<td>20µs</td>
<td>–</td>
</tr>
</tbody>
</table>

Cuadro 2.2: Parámetros de la respuesta temporal.

<table>
<thead>
<tr>
<th>Masa ablacionada</th>
<th>3.95e – 9kg</th>
<th>3.99e – 9Kg</th>
<th>1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impulso unitario</td>
<td>70e – 5N</td>
<td>70,04e – 5N</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

Cuadro 2.3: Parámetros numéricos.
Several geometrical and technological configurations were analysed, in order to obtain an optimal configuration. However, a compromise solution was chosen, case 12.

<table>
<thead>
<tr>
<th>cases</th>
<th>pros</th>
<th>cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Good bit impulse</td>
<td>High cap. required</td>
</tr>
<tr>
<td>5, 6, 11</td>
<td>Acceptable bit Imp. Better efficiency Lower inductance</td>
<td>High mass ablation, req. longer PTFE rod</td>
</tr>
<tr>
<td>15 to 18</td>
<td>Overall good perf.</td>
<td>Prohibitive size</td>
</tr>
</tbody>
</table>
PERFORMANCE ANALYSIS

Parameter relations

- The bit-impulse grows with the electrode radius ratio, i.e., it grows with the ablation area.
- A reduction of the circuit inductance results in a higher impulse.
- Ablated mass decreases with a longer acceleration chamber.
- Specific impulse increases with the acceleration chamber length.

Results: case 12

Geometrical parameters

- Central electrode radius: 3mm. Acceptable performance and good structural stiffness.
- External electrode radius: 15mm. Acceptable performance and relatively low volume.
- Acceleration channel length: between 25mm and 30mm. Good performance.

Electrical parameters

- Capacitors charge tension: 4000V. A higher voltage brings about issues that require a more complex design of the power electronics. A lower tension decreases excessively the impulse.
- Capacitors capacity: 1.8µF. A higher capacity does not improve significantly the impulse. A lower capacity does not supply enough energy.
PERFORMANCE ANALYSIS

Case 12 results

Capacitors voltage variation

Capacitors capacity variation
Optimization criteria
1. Bit-impulse criterion: enhance the impulse in order to reach the 100[μNs] required by pulse at a 3Hz discharge frequency.
2. Specific impulse criterion: obtain a high specific impulse, i.e. reach a efficient propellant mass utilization.

<table>
<thead>
<tr>
<th>Parámetros eléctricos</th>
<th>Parámetros geométricos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacidad $C$ [μF]</td>
<td>Radio electrodo central [mm]</td>
</tr>
<tr>
<td>Voltaje de carga $V$</td>
<td>Radio electrodo anular [mm]</td>
</tr>
<tr>
<td>Resistencia total $Ω$</td>
<td>Longitud electrodo central [mm]</td>
</tr>
<tr>
<td>Inductancia total total $nH$</td>
<td>Longitud electrodo anular [mm]</td>
</tr>
</tbody>
</table>

Cuadro 3.3: Parámetros del modelo de ingeniería P4S-2
Configuration
• Acceleration channel length: 0.025m
• Cathode diameter: 0.030m
• Anode diameter: 0.006m
• PTFE bar required length: 0.055m
• Capacitor voltage: 4000V
• Capacity: 1.8μF
• Number of pulses required: 7.885.700

Performances
• Bit impulse: 97μNs
• Specific impulse: 960s
• Energetic efficiency: 3.4%
Mathematical modelling and simulation
- A tool for evaluation performances of PPT has been obtained.
- The model shows some limitations, not only because of the model itself, but also due to the lack verification with more experimental data.
- The simulations have allowed to find relations between parameters, which show a remarkable match with specialized bibliography.
- Montecarlo method application has shown a high level match with performance analysis made by hand.

Performances
- A total impulse of 1500Ns is reached in fewer than $10^7$ discharges.
- A thrust of 0.29mN is obtained, over the 0.25mN required.
- The efficiency of 3.4% is rather low, while it is usual for qualified PPTs to have an efficiency of approximately 8%.