CIRA IMP-EP project:
Development and Validation of a 1D Model for Hollow Cathode Analysis and Design

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Outline

- Background
- CIRA IMP-EP program: overview
- CIRHET-250 Experimental Hall Thruster
- Orifice Hollow Cathode (OHC) - Preliminary Design Tool
  - Description
  - Validation
- Conclusions
- Future Development
**CIRA**, the **Italian Aerospace Research Center**, has been established to create technology know-how in order to support the Italian Aerospace Companies and contribute to the European aerospace development activities in cooperation with:

- National and International Institutions
- Universities
- Research Centers
- Companies

One of the main missions is to develop **strategic competences** and **know-how** in the field of **aerospace propulsion**.

At this moment, CIRA is involved in several national and international projects concerning **solid, liquid and electric propulsion** and intends to improve the **testing capabilities**, besides the theoretical and simulation aspects.
CIRA program on space electric propulsion[^1] is divided in three main lines:

**OR-1 Facilities**

- **<5kW**
  - MSVC
  - Design
  - Build
  - Commissioning
  - 2018

- **>5kW**
  - LSVC
  - Design
  - Build
  - Commissioning
  - 2020

**OR-2 Diagnostics**

**OR-3 Thrusters**
The low power Hall Effect Thrusters (HET) will be tested in MSVC in order to set-up advanced diagnostic.

The low-power HET, CIRHET-250, is in Preliminary Design Review Phase, and it has been designed according to HET scaling methodology*.

The design of CIRHET-250 has been preliminary verified by magnetic field, thermal and CFD analyses.

<table>
<thead>
<tr>
<th>CIRHET-250[2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Discharge Power</td>
</tr>
<tr>
<td>Nominal Thrust</td>
</tr>
<tr>
<td>Specific Impulse</td>
</tr>
<tr>
<td>Propellant</td>
</tr>
<tr>
<td>Cathode Location</td>
</tr>
<tr>
<td>Thruster Mass</td>
</tr>
</tbody>
</table>
A design tool for the cathode is necessary to develop the low power HET. In order to understand physical behavior and predict main design parameters, a simplified model has been developed.

A complete model of a thermionic hollow cathode requires:

- Plasma models (*Emitter insert region, Orifice region, Orifice-Keeper Region*)
- Thermal models

**Plasma Model Assumptions**

- Properties averaged in each control volume
- Steady state condition
- Quasi-neutral plasma, mixture of three perfect gases (thermalized electrons, singly-charged positive ions, and neutrals)
- Ions and neutrals at the same temperature of the cathode wall.
Two systems have been solved, to obtain plasma parameters:

- **Orifice Plasma**
  - Pressure Equation
  - Ion Flux Balance
  - Internal Power Balance
  -\( n_{e,0} \); \( T_{e,0} \); \( n_{0,0} \)

- **Insert Plasma**
  - Plasma Pressure Equation
  - Ion Flux Balance
  - Current Density Balance
  - Plasma Power Balance
  -\( n_{e} \); \( T_{e} \); \( n_{0} \); \( V_p \)

Actual version of the tool:

- Emission length \((L_e)\), emitter \((T_s)\) and orifice \((T_wo)\) wall temperatures are input (**not updated**)
- Emitter electron temperature \((T_e)\) is the convergence parameter which links the plasma models (**updated**)
- Verification of plasma conditions (Debye length, mean free paths calculations)
OHC Preliminary Design Tool - Description
MATLAB® GUI- Graphic User Interface

**CODE INPUT:**
- Geometry
- Operational ($I_d \times \dot{m}_{do}$)
- Propellant Properties
- Insert Properties (Richardson-Dushman, work function)
- Starting plasma properties values
- Wall Temperatures (emitter, orifice)

**CODE OUTPUT:**
- Emitter Region Plasma Properties
- Orifice Region Plasma Properties

**NEXT STEPS:**
- Updating emission length and wall temperatures (thermal model)
- Orifice tip-keeper Region Plasma Properties Model
### Xenon Cathodes

<table>
<thead>
<tr>
<th>Reference</th>
<th>NSTAR(^{[3]})</th>
<th>Wilbur-1984 (^{[4]})</th>
<th>Domonkos-1999 (^{[5]})</th>
<th>Albertoni-2013 (^{[6]})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Validation Plasma Region</strong></td>
<td><strong>Orifice</strong></td>
<td><strong>Insert</strong></td>
<td><strong>Orifice + Insert</strong></td>
<td><strong>Orifice + Insert</strong></td>
</tr>
<tr>
<td><strong>Available data</strong></td>
<td><strong>Num.</strong></td>
<td><strong>Exp./Num.</strong></td>
<td><strong>Exp./Num.</strong></td>
<td><strong>Num.</strong></td>
</tr>
<tr>
<td>Insert internal diameter [mm]</td>
<td>3.8</td>
<td>3.8</td>
<td>1.22</td>
<td>3</td>
</tr>
<tr>
<td>Orifice length [mm]</td>
<td>0.75</td>
<td>1.22</td>
<td>0.71</td>
<td>0.36</td>
</tr>
<tr>
<td>Orifice Diameter [mm]</td>
<td>0.28</td>
<td>0.76</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass flow rate, [mg/s]</td>
<td>0.36</td>
<td>0.127</td>
<td>[0.11 ÷ 0.23]</td>
<td>[0.3 ÷ 2]</td>
</tr>
<tr>
<td>Discharge Current [A]</td>
<td>3.26</td>
<td>[1.24 ÷ 4.26]</td>
<td>[0.75 ÷ 1.25]</td>
<td>[1 ÷ 3]</td>
</tr>
<tr>
<td><strong>Insert Material</strong></td>
<td><strong>Ba</strong></td>
<td><strong>Ta (dip-coated)</strong></td>
<td><strong>W (Doped)</strong></td>
<td><strong>LaB(_6)</strong></td>
</tr>
<tr>
<td>Richardson-Dushman cost. [10(^4) A/m(^2)·K(^2)]</td>
<td>1.5</td>
<td>120</td>
<td>60</td>
<td>29</td>
</tr>
<tr>
<td>Work function [eV]</td>
<td>1.56</td>
<td>2.25</td>
<td>2.3</td>
<td>2.66</td>
</tr>
</tbody>
</table>
**OHC Preliminary Design Tool - Validation**

**Orifice Plasma Model: **NSTAR cathode

<table>
<thead>
<tr>
<th>ORIFICE parameter</th>
<th>0-D model (CIRA calculation)</th>
<th>0-D model (Mizrahi(^7))</th>
<th>0-D model (Mandell and Katz(^8))</th>
<th>0-D model (Korkmaz and Celik(^9))</th>
<th>0-D model (Albertoni et al.(^6))</th>
<th>1-D model (Katz et al.(^10))</th>
<th>2-D model (Mikellides and Katz (^11))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Orifice inlet</td>
<td>Maximum reached value</td>
</tr>
<tr>
<td>(n_0(10^{23} \text{ m}^{-3}))</td>
<td>0.15</td>
<td>1.1</td>
<td>0.4</td>
<td>0.6</td>
<td>0.2</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>(n_e(10^{22} \text{ m}^{-3}))</td>
<td>0.77</td>
<td>2.7</td>
<td>1</td>
<td>0.7</td>
<td>0.7</td>
<td>2.8</td>
<td>6</td>
</tr>
<tr>
<td>(T_e (\text{eV}))</td>
<td>2.45</td>
<td>1.6</td>
<td>2.2</td>
<td>2.4</td>
<td>2.7</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>(n_e/(n_e+n_n))</td>
<td>0.34</td>
<td>0.2</td>
<td>0.18</td>
<td>0.1</td>
<td>0.24</td>
<td>0.09</td>
<td>0.24</td>
</tr>
</tbody>
</table>

- Electron temperature and density close to Albertoni\(^6\) and Korkmaz\(^9\) computations by an error less than 10%; neutral density is underestimated.

- Higher electron temperature along with lower plasma and neutral densities with respect to the predictions of the 0-D model by Mizrahi\(^7\), and the 0-D model by Mandell and Katz\(^8\) (this two models include the energy loss due to excitation events in the plasma energy balance, neglected in the present study).

- Better accordance with the values predicted by the 2-D model of Mikellides and Katz\(^11\) at the orifice outlet.
OHC Preliminary Design Tool - Validation
Insert Plasma Model: Wilbur cathode

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Code Input</th>
<th>Code Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilbur</td>
<td>$T_e$</td>
<td>$L_e, T_s$</td>
<td>$V_p, n_e$</td>
</tr>
<tr>
<td>CIRA</td>
<td>$L_e, T_s$</td>
<td>$T_e$</td>
<td>$V_p, n_e$</td>
</tr>
</tbody>
</table>

Experimental and Numeric Data
Wilbur \(^4\)

- Trends are well predicted (particularly those of plasma potential)
- With respect to Exp. Data: Overestimation of electron density; underestimation of Plasma potential
- Average wall temperature level in line with respect to Exp. Data and close to numerical data
- Emission Length increases with current and match the numeric data very well (almost within Exp. Data)
OHC Preliminary Design Tool - Validation
Insert Plasma Model: Domonkos cathode

- Trends well predicted
- Calculations close to experimental data (1.3mm distance to orifice @ 0.75A) except for electron density

Experimental Data – Domonkos [5]
Trends are well predicted
Orifice electron temperature changes with current (trend not detected by Domonkos)
Slight overestimation of electron number densities in insert and orifice regions
OHC Preliminary Design Tool - Validation
Insert and Orifice Plasma Model: Albertoni cathode

- Trends well predicted for every case
- Insert region: Electron number density overlapped to Albertoni\textsuperscript{\cite{Albertoni}} calculation;
- Orifice region: Electron number density close to Korkmaz\textsuperscript{\cite{Korkmaz}} data (except for 0.3mg/s test case);

Numeric Data – Albertoni\textsuperscript{\cite{Albertoni}} Korkmaz\textsuperscript{\cite{Korkmaz}}
CONCLUSIONS

- CIRA is expanding its testing capabilities with two new facilities for Electric Propulsion: MSVC (<5kW, by 2018) and L SVC (>5kW, by 2020)
- CIRA has started, from 2015, the acquisition of basic research competences and engineering design skills on EP devices
- A reduced-order numerical model describing the insert’s and orifice’s plasmas in an orificed hollow cathode has been developed as a quick tool for the design of thermionic cathodes. In this preliminary implementation walls’ temperatures and emission length are imposed.
- The results of the validation tests have been shown. They are in good agreement with both theoretical and experimental trends found in the literature.

FUTURE DEVELOPMENTS

- Dedicated Thermal model implementation: evaluation of the heat transfer mechanisms and the related temperature gradients along the cathode
- Modelling of plasma in the near tip cathode region
- Emission length updating
- Preliminary design of a specific cathode for the developed thruster (CIRHET-250)
- Experimental test campaign: validation of the tool (scheduled by the first half of 2018)


Thanks for your attention

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