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FIELD EMISSION ELECTRIC PROPULSION : EMISSION CHARACTERISTIC OF SLIT EMITTERS

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Abstract - Field emission electric propulsion is the technological application of the principle of liquid metal ion sources as thrusters in electric space propulsion. Research work sponsored by the European Space Agency (ESA) on the emission performance of a slit type field ion thruster is reported and discussed.

I. INTRODUCTION

Within ESA's research programme on electric propulsion, field emission electric propulsion using liquid caesium (Cs) as favoured propellant is of special importance; research and development work performed at ESTEC results in the slit emitter /1,2/.

When the surface of a liquid metal is subjected to a high electric field it is distorted into a cone or a series of cones which protrude more and more from the surface with increasing field strength.

When the local field reaches values of the order of $10^9 \text{V m}^{-1}$, atoms of the metal tip are ionized either by field desorption or field ionization; with the proper electric polarity, the free electrons are rejected into the bulk of the liquid metal while the ions are accelerated and expelled from the emitter by the same electric field which has ionized them, creating therefore the thrust.

Recent investigations /3,4/ have demonstrated the outstanding importance of both the residual gas atmosphere and the emitter preparation technique on the emission performance of slit emitters. Besides the emission site distribution /4/, the beam divergence is of considerable importance as it is directly connected to the specific thrust, the latter being a striking figure of merit of a field emission ion thruster.

II. THE SLIT EMITTER MODULE

The slit emitter module in principle consists of two symmetrical highly polished metal plates of the shape depicted in Fig.1. In one or both of the emitter halves there is milled a recess to be of use as a reservoir of the liquid metal (mostly Cs) supplied to the emitter module either by an open funnel or a feeding capillary tube. On certain regions of one of the inside faces there is sputter deposited a layer of nickel with a thickness of the order of $10^{-4} \text{m}$.

When the two halves are tightly clamped together they are separated by the thickness of this layer, thus forming a narrow slit of width $w$ and depth $d$ through which the liquid metal can flow and be transported to the edges of the slit by the action of capillary forces (Fig.2).
Until now, a number of emitter modules with slit lengths of 10, 30, 50 and 80 mm have been produced. The electrode configuration widely used to create the proper electric field at the emitter slit edge region is shown in Fig. 2. A plane accelerator electrode with an aperture of width 2b is mounted in a linear distance a of the emitter slit edge. Both emitter and accelerator are kept at voltages +U_E and -U_ACC respectively vs. ground potential in order to accomplish the electric field necessary to create and accelerate the ion beam.

Under the assumption that all of the charge transported from the emitter is released in form of singly ionized Cs atoms only (neglecting therefore the contribution of molecular ions which are found to contribute only about 16% to the charge transport) and assuming furthermore that all these ions are emitted normally to the plane of the accelerator electrode, the thrust F is then given

\[ F = \dot{m}^+ v_E \]  

where \( v_E \) is the exhaust velocity of the ions (i.e. the final velocity in field-free space) resulting from conservation of energy

\[ v_E = (2eU_E/m_+)^{1/2} \]  

\( U_E \) is the emitter voltage and \( m_+ \) is the ion mass. Relating the ion mass flow rate \( \dot{m}^+ \) to the emission current \( I_E \)

\[ \dot{m}^+ = I_E m_+ / e \]  

then the thrust is given by

\[ F = I_E (2eU_E / m_+)^{1/2} \]  

Contrary to the assumption made above of an one-dimensional beam one finds that for a slit emitter some divergence of the beam occurs in both the plane normal to the plane of the emitter slit as well as in the plane of the emitter, denoted by the azimuthal half-angle \( \theta \) and the transversal half-angle \( \psi \) respectively as being outlined in Fig. 1.

As the measured values of the thrust \( F \) always are below the theoretical ones defined by eq. (4), in an attempt to account of the beam divergence Bartoli et al. \( /1/ \) proposed a modified formula for the thrust

\[ F_\theta = F (\sin \theta / \theta) (\sin \psi / \psi) \]  

where it is assumed that there is an uniform distribution of ion trajectories within \( \theta \) and \( \psi \).
III. EXPERIMENTAL RESULTS AND DISCUSSION

In order to investigate the emission performance, a mini-emitter (emitter El) developed for this special purpose by ESTEC with a rather short emitter slit length $l = 1.10^{-2}m$ was inserted into an ultrahigh-vacuum equipment. The typical data for the emitter-accelerator geometry according Fig. 2 are as follows: $a = 6.10^{-4}m$, $2b = 4.10^{-3}m$, $d = 5.10^{-3}m$, $w = 1.2.10^{-6}m$.

For the first time a slit emitter was firing in vertical position, being supplied with Cs of high purity by means of a completely closed Cs-feeding system; such a closed propellant supply system requiring in principle no gravitational forces and allowing for firing of the emitter in any optimal direction also claims general interest in view of future space applications of liquid metal field emission thrusters [3].

In order to obtain homogeneous wetting of all internal surfaces of the Cs-feeding system and of the emitter itself, without emission an ultimate total background pressure of about $5.10^{-10}$ mbar was maintained within the vacuum chamber, the contribution of $H_2O$ and OH to this pressure being about 20% and 5% respectively.

The common phenomenological picture of emission within a current range of some $10^{-3}A$ always shows a rather large number (about 1200) of equidistant faint glowing zones of equal brightness spaced by about $7.5.10^{-6}m$ and distributed homogeneously along the emitter slit edge, the only exception being two much brighter luminous regions at the slit ends as well as some few less brighter sites occurring always at the same places. As the brightness of the luminous zone in front of the apex of an emission site depends on the emission current, one may conclude from this feature a homogeneous distribution of equidistant spaced identical emission sites superimposed by some few sites with higher emission current.

**Beam divergence**

The profile of the ion beam emanating from the emission sites situated along the emitter slit edge is recorded in both azimuthal and transversal direction by either pivoting the emitter around an azimuthal angle $\theta$ and rotate an ion probe around a transversal angle $\varphi$. Furthermore the azimuthal divergence of both the neutrals as well as atomic and molecular ions emanating from the emitter is measured by means of a quadrupole mass analyzer (QMA), the axis of the latter being coincident to the direction defined by the relations $\theta = 0^\circ$ and $\varphi = 0^\circ$.

The beam divergence in both azimuthal and transversal direction is outlined in the axionometric display shown in Fig. 3.

![Figure 3: Normalized azimuthal and transversal beam divergence profile of the emitter El as a function of the emission current $I_e$ ($U_{ACC} = -4.10^3V$, $a = 6.10^{-4}m$)](image-url)
The divergence profiles in azimuthal direction ($\psi = \text{const}$) correspond quite well to the shape obtained hitherto for the case $\psi = 0^\circ$, while the profiles in transversal direction ($\varphi = \text{const}$) show a pronounced dip between two maxima of different height at values of the transversal angle $\varphi = \pm 6^\circ$, resulting finally in a beam divergence characterized by a saddle surface. The two rather symmetric maxima in the transversal divergence profile may be attributed to pronounced side emission typically for this emitter.

According to the different possibilities of mass spectroscopic analysis of the constituents of the ion beam, the beam divergence was measured considering the thermal neutral particle flux ($\text{Cs}^0\text{TH}$) without ion emission, the neutral particle flux ($\text{Cs}^0\text{FI}$) during ion emission as well as the ionized particle flux ($\text{Cs}^+\text{FI}$), the results being shown in Fig. 4.

![Figure 4: Normalized azimuthal beam divergence profiles of the emitter El for the different constituents of the beam ($I_E = 5.10^{-3} A$, $V_{\text{acc}} = -4.10^3 V$, $a = 6.10^{-4} m$)](image)

As the neutral particle flux ($\text{Cs}^0\text{TH}$) emanates from the whole free Cs-surface at the emitter slit orifice, a cosine-distribution ($\cos \varphi$) according to Lambert's law may be expected for the beam divergence. Measurements result in a slightly broader beam divergence profile; this feature is attributed to the meniscus of Cs protruding out of the emitter slit orifice also without any applied voltage and to the wetting of the rounded emitter slit edges, allowing a certain fraction of vapour emanating perpendicular to the plane of the emitter slit.

The most striking result is obtained for the neutral particle flux ($\text{Cs}^0\text{FI}$). The divergence profile of the beam to a certain extent is between the rather narrow distribution of the ionized particle flux ($\text{Cs}^+\text{FI}$) and the cosine distribution; the results of different measurements show a rather large scatter, the values of the FWHM being between about $97^\circ$ and $107^\circ$. The divergence profile shows a cut off at $\varphi = 60^\circ$ due to the shadow effect of the accelerator electrode.

If one assumes the neutral particle flux ($\text{Cs}^0\text{FI}$) being created mainly due to dissociation of microdroplets by electric forces, the observed beam profiles possibly may be explained by a superposition of the strictly directed velocity components of initially charged micro-particles in the accelerating electric field with the rather uniform distributed velocity components of neutral particles due to the dissociation process itself; also elastic collision processes between ions and neutral atoms may play some distinct role.

The beam profile of the ionized atomic particle flux ($\text{Cs}^+\text{FI}$) finally is nearly identical to the divergence profiles obtained by ion probe measurements; similar results were obtained for molecular ions $\text{Cs}_2^+$ and $\text{Cs}_3^+$. 
Thrust and specific power

In the present experiment there is no possibility of a direct measurement of the thrust of the emitter modules. In order to obtain a comparative value, the thrust is calculated according eq.(4), assuming for simplicity singly ionized atoms Cs+ only.\(^1\)

With \(m_{Cs} = 2,208.10^{-28} \text{kg}\), eq.(4) is given

\[
F = 1,66.10^{-3}I_\text{e}U_\text{e}^{1/2}
\]  

(6)

Considering further the influence of the beam divergence one finds

\[
F_\text{e} = SF
\]  

(7)

where \(S\) is a divergence factor given according eq.(5).

From Fig. 3 one finds for a wide range of the emission current nearly constant values of the azimuthal half angle \(\varphi = 50^\circ\) and of the transversal half angle \(\Theta = 35^\circ\).

For a comparable emitter (ESTEC1\#1) yet having an emitter slit length \(l = 5.10^{-3}\text{m}\), Bartoli et al.\(^1\) measured the thrust by means of a balance at a constant value of the emission current \(I_\text{e} = 1.10^{-2}\text{A}\); for this current the beam divergence was evaluated to be about \(\varphi = 35^\circ\) and \(\Theta = 15^\circ\). In a voltage range of \(U_\text{e}\) between \(6.10^3\) and \(1.2.10^4\text{V}\), good agreement was found between the measured thrust and the calculated values according eq.(7).

In order to compare the emission performance of the present emitter E1 and the emitter ESTEC1\#1, for the same values of the specific emission current \(I_\text{e}' = I_\text{e}/l = 2.10^{-3}\text{Acm}^{-1}\) and an emitter voltage \(U_\text{e} = 1.10^4\text{V}\), characteristic emission parameter are summarized in Tab.1.

Besides the divergence factor \(S\), there are indicated in Tab.1 as follows: The thrust \(F_\text{e}\), the total power input \(P\), the specific thrust \(F_\text{e}'\) normalized to emitter unit length

\[
F_\text{e}' = F_\text{e}/l
\]  

(8)

and finally the specific power \(P'\) which is given by

\[
P' = P/F_\text{e}
\]  

(9)

The total power input \(P\) to the emitter, neglecting the almost tiny contribution of the accelerator power loss then is given by

\[
P = I_\text{e}U_\text{e}
\]  

(10)

For comparison, furthermore with \(S = 1\) and \(l = 5.10^{-3}\text{m}\) theoretical values of both the thrust \(F_\text{e}\) and the specific thrust \(F_\text{e}'\) are indicated; the specific power \(P'\) follows from eqs.(6) and (10)

\[
P' = P/F = 6.10^2U_\text{e}^{1/2}
\]  

(11)

<table>
<thead>
<tr>
<th>(S)</th>
<th>(\varphi)</th>
<th>(\Theta)</th>
<th>(F_\text{e}(N))</th>
<th>(P(W))</th>
<th>(F_\text{e}'(\text{Ncm}^{-1}))</th>
<th>(P'\text{(WN}^{-1}))</th>
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<tr>
<td>Theory</td>
<td>-</td>
<td>-</td>
<td>1,00</td>
<td>1,66.10^{-3}</td>
<td>-</td>
<td>3,3.10^{-4}</td>
</tr>
<tr>
<td>ESTEC1#1</td>
<td>35^\circ</td>
<td>15^\circ</td>
<td>0,93</td>
<td>1,55.10^{-3}</td>
<td>100</td>
<td>3,1.10^{-4}</td>
</tr>
<tr>
<td>E1</td>
<td>50^\circ</td>
<td>35^\circ</td>
<td>0,87</td>
<td>2,88.10^{-4}</td>
<td>20</td>
<td>2,9.10^{-4}</td>
</tr>
</tbody>
</table>

\(^{1}\) Considering the actual percentage of dimers and trimers (Cs\(_2^+\), Cs\(_3^+\)) in the ion beam, the share of the latter is about 16% on the charge transport, about 30% on the mass transport and about 22% on the thrust.
Measurements on the emitter ESTEC1,1 were performed up to a maximum emission current of $I_e = 1.5 \times 10^{-9} \text{A}$ /1/; this value, corresponding to a specific emission current $I_e' = 3.1 \times 10^{-3} \text{Acm}^{-2}$, possibly is due to current saturation. On the other side, the emitter E1 operates up to a specific emission current $I_e' = 5.1 \times 10^{-3} \text{Acm}^{-2}$ without any saturation effect, the latter value only be due to the limited current capacity of the high voltage power supply. For this limiting value and with $U_e = 1.10^4 \text{V}$, the emission parameter according Tab.1 for the emitter E1 now are

$s = 0.87$, $F_e = 7.2 \times 10^{-4} \text{N}$, $P = 50 \text{W}$, $F_e' = 7.2 \times 10^{-4} \text{Ncm}^{-1}$, $P' = 6.94 \times 10^4 \text{Wcm}^{-2}$

In conclusion, with regard to the specific power or the power to thrust ratio, which is one of the most decisive emission parameter in view of a future application of liquid metal field emission thrusters in space, the calculated emission performance of the emitter E1 is only fairly below that of the emitter ESTEC 1,1; this discrepancy is due to a somewhat higher beam divergence.

On the other side, the capability of the emitter E1 to operate at rather high values of specific emission current and specific thrust respectively successfully was demonstrated. This outstanding emission performance may be contributed to the excellent wetting properties and the nearly homogeneous emission site distribution inherent to the latter emitter.

ACKNOWLEDGEMENTS

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REFERENCES

/3/ J.Mitterauer, "Field emission electric propulsion: Spectroscopic investigations on slit emitters"