Development of a Telemicroscopy Diagnostic Apparatus and Erosion Modelling in Hall Effect Thrusters

IEPC-2009-036

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

Tommaso Misuri1, Andrea Milani2 and Mariano Andrenucci3
Alta Spa, Ospedaletto, Pisa, 56121, Italy

Abstract: A new diagnostic apparatus and a numerical code have been developed by Alta Spa to tackle the problem of Hall Effect Thruster erosion. The diagnostic system consists of a couple of cameras that provide optical measurements of the HET channel, revealing how its shape changes in time when the thruster is firing. Besides, the diagnostic system has been designed to be as versatile as possible and can be employed also for measuring the erosion of ion engine grids with minor modifications. The numerical code is based on a Monte Carlo simulation of the ion sputtering phenomenon inside the acceleration channel. The code has been validated using existing data and it turns out to be a valuable tool not only for predicting HET erosion, but also to investigate possible solutions for erosion reduction (changes in geometry or thruster operational parameters). Of course, the future development of the numerical code is tightly connected with the completion of the diagnostic apparatus, since further comparisons between theoretical predictions and experimental data are necessary for a full validation of the erosion model.

Nomenclature

\[ A \quad \text{Channel cross sectional area} \]
\[ E \quad \text{Electric field intensity} \]
\[ m_i \quad \text{Ion mass} \]
\[ n_i \quad \text{Ion particle density} \]
\[ n_n \quad \text{Neutral particle density} \]
\[ \dot{n}_{ion} \quad \text{Ionization rate} \]
\[ q \quad \text{Elementary charge} \]
\[ r \quad \text{Channel radius} \]
\[ S \quad \text{Sputtering yield} \]
\[ t_w \quad \text{time-to-wall} \]
\[ u_i \quad \text{Ion velocity before any collision} \]
\[ u_{i\_coll} \quad \text{Ion velocity after a collision with a neutral} \]
\[ u_{i\_wall} \quad \text{Ion velocity when} \]
\[ u_n \quad \text{Neutral velocity} \]

1 Research Engineer, Alta Spa, tmisuri@alta-space.com
2 Research Engineer, Alta Spa, amilani@alta-space.com
3 Professor of Electric Propulsion, Dipartimento di Ingegneria Aerospaziale Università di Pisa, CEO ALTA Spa, AIAA Senior Member, mandrenucci@alta-space.com
The 31st International Electric Propulsion Conference, University of Michigan, USA  
September 20 – 24, 2009

\[ u_{\text{coll}} \quad \text{Neutral velocity after a collision with an ion} \]

\[ V \quad \text{Electric potential} \]

\[ z \quad \text{Axial coordinate (distance from the anode)} \]

\[ \alpha_{\text{coll}} \quad \text{Random number } \in [0, 2\pi] \]

\[ \alpha_{\text{vel}} \quad \text{Random number } \in [-1, 1] \]

\[ \beta \quad \text{Wall inclination angle} \]

\[ \varepsilon_i \quad \text{Ion energy} \]

\[ \phi_{\text{lw}} \quad \text{Angle of impact with the wall (ion-wall collisions)} \]

\[ \sigma_{\text{in}} \quad \text{Ion-neutral collision cross section} \]

\section{I. Introduction}

Grid erosion for ion engines and channel wall erosion for Hall effect thrusters are phenomena which severely limit their lifetime. A better understanding of these phenomena is necessary to design devices able to operate with a high efficiency for thousands of hours, as requested by almost every mission involving low thrust propulsion. Many theoretical models have been developed in recent years, both for predicting HET channel erosion\textsuperscript{1,2,3,4,5} and ion engine grid erosion\textsuperscript{6,7}. However it is necessary to integrate them with experimental data, in order to check and validate the theoretical results. A comparison with experimental data is essential to refine the coefficients often employed in such models and improve their overall accuracy.

In this framework, a new diagnostic apparatus has been designed by Alta to investigate erosion phenomena affecting HET ceramic channel and ion engine grids. The whole system is mounted inside the vacuum chamber, this being a major benefit for this kind of measurements since it allows us to have an optimal view of the thruster and to operate with no need of opening the vacuum chamber.

The present work is focused on the diagnostics of HET erosion and it is basically divided into two parts. In the first part an overall description of the diagnostics apparatus is given, together with a brief explanation of its working principles. In the second part a numerical model for prediction of HET channel erosion is presented. This model has been developed in parallel with the design of the experimental apparatus, in order to compare the results coming out from computer simulations with real data. After a full validation, the numerical model could be effectively employed in the design of new thrusters (for lifetime estimation or for studying possible modifications aimed at controlling/reducing the erosion).

\section{II. Advanced Diagnostic System for HET Erosion Measurement}

The diagnostic system object of the present work has been designed with the purpose of reconstructing the shape of a Hall effect thruster channel at different instants during its operational lifetime. Reconstruction of the channel shape is possible starting from a series of images of the channel walls acquired by a camera at different times. A laser light is pointed at the insulator walls and sheds a bright line on them. When the ceramic material is eroded, the line projected by the laser on the walls changes its shape. Comparing images taken at different instants it is possible to reconstruct the real profile of the insulator wall from the change in shape of the projection of the laser light on the wall. Actually, two cameras and two lasers are employed here, one laser-camera system focused on the external wall of the channel and the other one focused on the internal wall.

The system is placed inside the vacuum facility, to have a perfect view of the thruster and to avoid any contamination due to the external environment when the erosion measurement is performed.

\subsection{A. Diagnostic System Architecture}

The diagnostic system for HET erosion measurement consists of a two cameras mounted on a movable structure connected to the thrust balance (see fig. 1). The motion is obtained through three separate stepper motors. Two motors allow the mounting arm to horizontally translate along a linear guide and to rotate around a vertical axis. A third motor is employed to rotate the camera support around its axis. With three degrees of freedom, the system can be successfully used on different thrusters, provided their size stays within definite limits (maximum channel external diameter of 20 cm). For bigger devices the whole structure should be redesigned at a larger scale.
The system is designed to remain in a parking position while the thruster is firing, in order not to interfere with the plasma plume (see fig. 2). When the thruster stops firing, the mounting arm is moved in front of the thruster and images of the insulator channel are recorded by the cameras. The two cameras, together with the laser lights, are the core of the diagnostic system. Since the cameras are not vacuum compatible, they are sealed in pressurized aluminum boxes (see fig. 3). Each box also encloses a linear actuator to focus the camera when measurements are taken at different distances from the target. Box viewports are protected by shutters. Each shutter is controlled by a small stepper motor placed outside the box and it is opened only for the time necessary for image acquisition. Using a shutter has been deemed necessary even if the whole system is not directly exposed to the plasma jet during thruster operation. Actually, graphite sputtered from the chamber walls can deposit on the viewing ports if they are left unprotected and this would prevent any further measurement.
Although the present paper is focused on HET erosion measurement, it is interesting to point out that this diagnostic system has been designed also to perform measurements of grid erosion for GIEs. For such task there is no need of a 3D image reconstruction method and laser lights are then unnecessary. A single camera, surrounded by four LEDs to illuminate the target, is enough for detecting the erosion of grid holes for a GIE. This camera has optical characteristics that are slightly different from the cameras employed for HET erosion measurements. The diagnostic system can be transformed from HET configuration into GIE configuration simply unmounting the support with the two cameras from the top of the main arm and substituting it with another sub-assembly featuring the GIE camera (see fig. 4 for a sketch of this alternative configuration).

B. Diagnostic System Working Principle: 3D Image Reconstruction Method

Structured light systems are widely used for three-dimensional shape reconstruction. Here the HET inspection is based on the homographic reconstruction of a surface profile after system calibration with a known target. The purpose is to obtain the profile of the channel ceramic edge from the image of a projected laser line. Knowing the position of the camera reference frame and the laser frame, it is possible to reconstruct the 3D scene as the intersection between the laser plane and the projection of the points from the CCD to the scene.

Calibration process is necessary to acquire all the key-parameters of the system, such as the laser plane orientation w.r.t. the camera optical axis. These parameters are the input for image-processing software, which fulfills the task of reconstructing the real shape of the target. A sketch representing the diagnostics working principle
is shown in fig. 5. Obviously, the overall accuracy of the measurement system is strictly dependent on the accuracy of the calibration procedure.

![Diagram of diagnostic system for 3D image reconstruction](image)

**Fig. 5: Working principle of a diagnostic system for 3D image reconstruction**

The rotating motion of the camera support around its own axis is fundamental for acquiring images relative to different thruster cross sections.

### C. Preliminary Tests to Assess the Capabilities of 3D Image Reconstruction Method

A number of preliminary test have been carried out to assess the capabilities of the image reconstruction method. One of the main concerns was about the resolving power of the cameras. To answer this question the following experiment has been set-up. A camera and a laser have been placed on an optical table, together with a sample prism used for calibrating the system. The calibration prism has been mounted on a horizontal translation stage and, after calibration procedure is over, it has been moved step by step along the translation stage. The prism has been moved of several steps, each step with a length ranging from 25 μm to 0.4 mm. Every displacement has been successfully detected by the diagnostic system, proving its capability of making measurements in the micrometric range (~10 μm). An image of the experimental set-up is displayed in fig. 6.

![Experimental set-up](image)

**Fig. 6: Experimental set-up to test the capability of the diagnostic system when working in the micrometric range**
III. Monte Carlo Erosion Model for Hall Effect Thrusters

Erosion process in Hall effect thrusters is still an open issue and a full understanding of the underlying phenomena has not yet been achieved. In the present work, ion sputtering has been assumed to be the main responsible of channel wall erosion in this kind of thrusters. When highly energetic ions impinge on the walls of the acceleration channel, some of the wall material is sputtered away as a consequence of the collision. Like thousands of bullets, ions continuously hit the walls causing their premature erosion. A proof which supports ion sputtering as the main erosion mechanism, is that erosion is concentrated at the end of the channel (where the ions are highly energetic), while it is negligible in the first part in the channel (where bulk ionization has yet to take place and ions have a lower energy). According to the model adopted, ions move axially along the acceleration channel under the effect of the applied electric field. It is because of collisions with neutral particles (always present in the plasma flow) that they can be scattered towards the side wall.

D. Model Description

The model has been developed after the work of Manzella, although several substantial modifications have been introduced. It is a 1D model for what concerns the plasma flow analysis, while it relies on a Monte Carlo strategy to simulate ion-neutral collisions and their effect.

\textbf{Plasma Flow Modelling:}

The basic equations adopted to describe the plasma flow along the channel are:

\begin{align*}
\text{Velocity of neutral particles:} \quad u_n &= \text{const} \quad (1) \\
\text{Ion velocity:} \quad u_i (z) &= \sqrt{\frac{2q(V(z) - V_0)}{m_i}} \quad (2) \\
\text{Continuity equation:} \quad \frac{d}{dz}(u_i n_i A) &= n_{\text{ion}} A = -\frac{d}{dz}(u_n n_n A) \quad (3)
\end{align*}

Ion and neutral number densities are given as initial conditions, as well as the velocity of the neutral particles (which is then held constant throughout the channel). Ions are accelerated by the applied potential difference, which is supposed to be known and is shown in fig. 7 for an SPT-100 like thruster. It has to be noticed that the channel cross section, \( A \), is not constant since it is going to get larger and larger due to the erosion. Ionization takes place along the channel and is described by the generation term \( n_{\text{ion}} A \).

![Fig. 7: Potential drop along the HET channel](image-url)
The previous set of equations is necessary to calculate number density and velocity for ions and neutrals in every section of the thruster. Such parameters are required to define the ion-neutral collision cross section and to estimate the energy of the ions impinging on the walls.

Ion-neutral Collisions:

Since ions are assumed to be scattered towards the wall as a consequence of collisions with neutrals, modeling ion-neutral interaction is of primary importance. A statistical approach, based on a Monte Carlo method, has been chosen to describe how the direction of an ion changes after a collision with a neutral. When a fast ion bumps into a slow neutral atom, it is scattered in a different direction but the magnitude of the relative velocity between the ion and the atom is assumed to remain constant. The relative velocity only changes its direction after the collision and it does so in a random way. The introduction of two random factors is necessary for a proper description of the collisional process: the post-collision angle in azimuthal direction, $\alpha_{coll}$ (a random angle in the interval $[0, 2\pi]$) and the magnitude of the ion axial velocity after the collision, $\alpha_{rel}$ (a random number in the interval $[-1,1]$). Ion radial and axial velocities after the collision are given by equations (4) and (5):

\[
\begin{align*}
    u_{\text{coll, ax}} &= \frac{1}{2}(u_i + u_n) + \frac{1}{2}(u_i - u_n)\alpha_{col} \\
    u_{\text{coll, rad}} &= \sqrt{1 - \alpha_{col}^2} \cos(\alpha_{coll})
\end{align*}
\]

Ion and neutral masses are assumed to be equal and the relative velocity before the collision is assumed to be purely axial.

$\alpha_{rel}$ equal to -1 means that the ion has bumped frontally with the atom and has been almost stopped by the collision (see that for $\alpha_{rel} = -1$ the radial velocity after the collision is always nil irrespective of the random value of $\alpha_{coll}$; $\alpha_{coll}$ makes no sense at all for this special condition).

$\alpha_{rel}$ equal to 1 means that the ion has just brushed the neutral atom without changing its direction nor its velocity which remains completely axial (no collision limit).

For every other value of $\alpha_{coll}$ the ion-neutral relative velocity takes a non-axial direction.

After having thoroughly investigated the effect of a single ion-neutral collision, it is necessary to estimate how many collisions take place in each section of the channel per second. To this purpose ion-neutral collision cross section, $\sigma_{in}$, has to be introduced:

\[
\sigma_{in} = 1.69 \cdot 10^{-18} - 2.77 \cdot 10^{-19} \cdot \log(u_i - u_n)
\]

The total number of collisions which take place in an elementary portion $dz$ of the channel in one second is given by the ion number-flow-rate times the probability for a single ion to hit a neutral atom in the distance $dz$:

\[
N_{\text{coll}} = (n_i u_i A_z) (n_i \sigma_{in} dz)
\]

Ion-wall Collisions:

Equation (7) gives the total number of collisions per second that occur between $z$ and $z+dz$. Of course, by no means this is the number of ions that hit the wall between $z$ and $z+dz$. A great part of the scattered ions will not even hit the wall at all, being scattered of too small an angle. The trajectory of each ion after a collision has to be separately investigated in order to predict if it is going to hit the wall and where (see fig. 8). Besides, the angle of incidence of the ion-wall collision has to be evaluated.

Thus, after every simulated collision, the motion of the ion has been tracked to determine its trajectory. To make the model more realistic, we have introduced a third random factor: the radial position of the collisional event. Starting from the point where the collision happened and taking the post-collision velocities as initial conditions, the ion motion has been described with the classic equations of uniformly accelerated motion. Since the wall radius, $r_w(z)$, is known, it is possible to estimate the time, $t_w$, required for the ion to reach the wall using an iterative
method (an iterative method is required because the ion will not necessarily impact with the wall in the same section where the ion-neutral collision took place; so the radial distance it has to cover is unknown, because it depends on \( r_{\text{impact}} \) and \( z_{\text{impact}} \) has in turn to be determined studying the ion motion). Once \( t_{w} \) has been determined, ion axial velocity at the wall can be easily calculated considering that the axial electric field is the only force acting on the particle:

\[
\begin{align*}
  u_{i,\text{wall,ax}} = u_{i,\text{coll,ax}} + t_{w} \frac{E_{q}}{m_{i}}
\end{align*}
\] (8)

If we assume the radial ion velocity not to change any more after the collision (no radial forces acting on the particle in the time interval \( t_{w} \)), we get the following expression for the effective incidence angle of the ion with the wall:

\[
\phi_{iw} = \tan^{-1} \left( \frac{u_{i,\text{wall,ax}}}{u_{i,\text{coll,rad}}} \right) + \beta(z_{iw})
\] (9)

\( \beta \) represents the inclination of the wall and it is a factor that has to be considered when the erosion has significantly changed the shape of the channel. The effective incidence angle is between \(-\pi/2\) and \(+\pi/2\), with \( \phi_{iw} = 0 \) for impacts normal to the wall.

The axial coordinate of wall impact is given by equation (10). Of course, the material eroded will be removed from the channel at the coordinate of the ion-wall impact, \( z_{iw} \).

\[
\begin{align*}
  z_{iw} &= z_{in} + u_{i,\text{coll,ax}} \cdot t_{w} + \frac{1}{2} \left( \frac{qE_{q}}{m_{i}} \right) t_{w}^2
\end{align*}
\] (10)

\( z_{iw} > z_{\text{exit section}} \) means that the scattered ion has exited the channel without impacting with the wall.

\[ \text{Fig. 8: Scattering phenomenon inside the HET channel} \]

**Evaluation of Wall Erosion:**

The amount of insulator material sputtered after an ion-wall collision (in mm\(^3\)) is given by equation (11). It depends on the energy of the impinging ion and on the angle of incidence with the wall. The material considered here is Boron Nitride (BN), which is the most commonly employed material for building HET acceleration channels.

\[
V_{\text{erosion single i-w collision}} = S(e_{i}, \phi_{iw}) q
\] (11)

where \( q \) is the ion charge and \( S \) is the sputtering yield (expressed in [mm\(^3\)/C]).
The sputtering yield, $S$, has been modelled using the semi-empirical formula derived by Gamero¹ and based on the theory of Yamamura and Tawara²:

$$S = \left( 0.0099 + 6.04 \cdot 10^{-6} \varphi_{iw}^2 - 4.75 \cdot 10^{-8} \varphi_{iw}^4 \right) \sqrt{\varepsilon_j \left( 1 - \frac{58.6}{\varepsilon_j} \right)^{2.5}}$$

Equation (12) estimates the material sputtered after a single ion-wall collision. To have a global evaluation of the erosion, we must remember that in each section of the thruster a huge number of random collisional events take place every second. Of course, only a fraction of them can be simulated with our Monte Carlo model. Let be $Y$ the number of ion-neutral collisions simulated in each section over a time $dt$. The erosion, in terms of mm³, caused by the ions scattered in $z_{in}$ (coordinate of the ion-neutral collision) in the time interval $dt$ and hitting the wall in $z_{iw}$ (coordinate of the ion-wall collision) is given by the following equation:

$$V_{erosion}(z_{iw}) = \left( S(e_i, \varphi_{iw}) q \right) N_{coll}(z_{iw}) dt$$

Notice that the sputtering yield is maximum for high incidence angles and that ions with energies lower than 58 eV are assumed not to cause erosion at all (58 eV is the activation energy for sputtering in the HPHall model developed by Gamero).

Fig. 9: sputtering yield as a function of the ion energy for impacts normal to the target surface

Equation (11) estimates the material sputtered after a single ion-wall collision. To have a global evaluation of the erosion, we must remember that in each section of the thruster a huge number of random collisional events take place every second. Of course, only a fraction of them can be simulated with our Monte Carlo model. Let be $Y$ the number of ion-neutral collisions simulated in each section over a time $dt$. The erosion, in terms of mm³, caused by the ions scattered in $z_{in}$ (coordinate of the ion-neutral collision) in the time interval $dt$ and hitting the wall in $z_{iw}$ (coordinate of the ion-wall collision) is given by the following equation:

$$V_{erosion}(z_{iw}) = \left( S(e_i, \varphi_{iw}) q \right) N_{coll}(z_{iw}) dt$$

That is the effect of a single ion-wall collision times the ratio between the total number of collisions taking place in $z_{in}$ over a time $dt$ and the number of collisions actually simulated with our numerical code ($Y$).

The correspondent variation of the channel radius in $z_{iw}$ can be obtained as:

$$r(z_{iw}) = \sqrt{(r_{old}(z_{iw}))^2 + \frac{1}{2} \cdot V_{erosion}(z_{iw}) \cdot \pi \cdot dz}$$

The sign $\pm$ depends on which wall is the target (+ for the outer channel wall, - for the inner wall). Adding the effects of all the collisional events simulated in all sections for each time interval $dt$, it is possible to obtain the
channel radius (inner and outer) at every axial coordinate after a given operational time. Thus, the whole channel shape can be reconstructed and plotted at any desired instant.

**Neutral-Wall Collisions:**

The Monte Carlo model here implemented follows also the scattered neutrals in their path towards the side walls and it takes into account their damaging effect. Neutral velocity after a collision with an ion can be easily obtained from equations (15) and (16), reminding that the momentum of the ion-neutral-system must be conserved through a collision. We can write:

\[
\begin{align*}
    u_{n,\text{coll,ax}} &= (u_i + u_n) - u_{l,\text{coll,ax}} \\
    u_{n,\text{coll,rad}} &= -u_{l,\text{coll,rad}}
\end{align*}
\]

Knowing the components of the neutral particle velocity after the collision and considering that electric field has no effect on these particles, it is trivial to locate the section where they will impact with the wall and the angle of impact (which is just the complement of the scattering angle plus the wall inclination angle).

Simulations show that neutrals have a minor influence on the overall erosion because they impact with the walls with a lower energy w.r.t. the ions (which continue to be accelerated also after the scattering collision with an atom).

**E. Simulation Results and Comparison with Existing Data**

To test our erosion model, several simulations have been run considering SPT-100 as reference thruster. The reason for this choice is simply that SPT-100 is one of the few Hall thrusters whose erosion data can be found in literature\textsuperscript{10}. The parameters that have been selected for simulating the ion sputtering erosion are listed in tab. 1:

| Inner Radius of the channel | 35 [mm] |
| Outer Radius of the Channel | 50 [mm] |
| Channel Length              | 22 [mm] |
| Mass Flow Rate              | 5 [mg/s] |
| Applied Potential Difference| 300 [V] |

**Table 1: Geometric and operational parameters chosen for numerical simulations (SPT-100)**

Simulation results up to four thousands hours of operation are reported in fig. 10, while in fig. 11 and 12 numerical results are compared with experimental data for both the inner and the outer channel wall.

![Fig. 10: Erosion of outer channel wall after 4000 hrs of operation (numerical results)]
Fig. 11: Comparison between numerical and experimental results for SPT-100 – inner wall

Fig. 12: Comparison between numerical and experimental results for SPT-100 – outer wall
Erosion saturation mechanism:
It is well known that the erosion rate is higher at the beginning of thruster life and it decreases in time. This effect is apparent also looking at fig. 13 and 14, where the outer channel radius and the erosion rate are plotted vs. time.

There are two distinct factors that lower the erosion rate during the thruster lifetime:

- Wall inclination: erosion causes the walls to be divergent in the last part of the channel; as a consequence it would be more and more likely for the scattered ions to escape the channel without impacting with the walls.

- Reduction of particle number density: this is due to the enlargement of the channel cross section and has the immediate consequence of a reduction in the number of ion-neutral collisions.
Besides when the distance between the walls grows, the electric field has, on average, more time to act on scattered ions and to axially accelerate them outside the thruster.

IV. Conclusions

An advanced diagnostic system for detecting erosion effects on HET channels has been designed. The objective is to obtain a 3D reconstruction of the channel profile at different times during the HET operational life. This diagnostic system has already proven its capability of detecting micrometric displacements in a preliminary test carried out using simply a camera-and-laser sub-assembly.

Together with the diagnostic system a numerical model for erosion prediction has been developed. The model is based on a Monte Carlo simulation of the ion sputtering phenomenon inside the HET channel. With respect to other existing similar models, the present code takes into account the effect of wall inclination, calculates the coordinate of each ion-wall impact (which can be different from the coordinate of ion-neutral collision) and allows for a progressive ionization along the channel. Electric field acts on the ion also in the post-scattering phase, bending its trajectory and changing the angle of impact with the wall. In addition, a second Monte Carlo sampling has been nested in the model in order to simulate ion-neutral collisions at different radial coordinates.

Model results have been compared with experimental erosion data for an SPT-100 thruster. Theoretical and experimental values for erosion depth after up to 1000 hrs of operation seem to be in good agreement. A simulation of a longer firing time has been performed as well, successfully pointing out the presence of a saturation mechanism for the erosion process.

Acknowledgments

Authors would like to thank SPACELIGHT Srl, which is in charge for the optical part of the diagnostic (cameras and lasers) and has developed the necessary software for 3D profile reconstruction.

References


