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Model for Predicting the Lifetime of a Hall Effect Thruster

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Erosion of the acceleration channel is the main lifetime limiting factor for Hall Effect Thrusters (HETs). Impacting ions damage the wall insulation that protects the magnetic circuitry from the plasma. To improve HET technology, it is necessary to simulate plasma behavior inside the channel, and associated erosion rates. This work presents a 2-dimensional Particle-in-Cell model, developed to predict channel wall erosion in Hall thrusters, using an SPT-100 as reference thruster, and providing estimations in good agreement with experimental values. The model allows for evaluation of different erosion mechanisms, both combined as individually. From different simulation results, erosion due to the sheath conditions has proven to be the dominant source for wall erosion.

Nomenclature

A	=	cross-sectional area
dt	=	iteration time step
dx, dz	=	spatial step
e	=	electron
E	=	energy
i	=	ion
m	=	mass
n	=	particle density
q	=	elementary charge
S	=	sputtering yield
T	=	temperature
u, v	=	velocity
w	=	wall
Γ	=	particle flux
ν_i	=	ionization frequency
σ_e	=	secondary electron emission
σ_{in}	=	collision cross-section
φ	=	electric potential
BN	=	Boron Nitride
FD	=	Flow Divergence
PS	=	Particle Scattering
SE	=	Sheath Effect
SEE	=	Secondary Electron Emission

I. Introduction

Hall Effect Thrusters are a type of electric propulsion, used for accurate attitude and orbit control which demands low thrust and high specific impulse[3,7,12]. For such missions, typical lifetimes of about 3000 hours[3] are needed, which is easily satisfied by the 7000 hour lifetime of, for example, the SPT-100[2,12]. Hall thrusters have proven easy throttleability and scalability[3,7], and exploiting their capabilities in an expanded range of missions, requires further investigation of their performance and extension of their lifetime.

Different than for chemical propellants, for which the propellant storage and mass limit the operation period, the lifetime limiting factor for many electric thrusters is the interaction of the structure with the plasma. Among them, HETs suffer from erosion of the discharge channel. The channel wall insulation protects the magnetic circuit from hazardous particle. When the magnetic circuitry is exposed to the plasma, overheating or further degradation of the system leads to decreased thruster performance. Once the protecting insulation is fully eroded, the end of the thruster's lifetime is reached.

As life tests are time-consuming and expensive, monitoring wall degradation demands for computational erosion models. Such programs serve two purposes. First, they predict the lifetime and plasma behavior for a given thruster configuration. Second, they provide design requirements to meet a given set of specifications. Data can be acquired repeatedly for different conditions, cost-free, and in a short period of time.

Different than simplified erosion models[6,7,11] which only attribute erosion to particle collisions and include other phenomena by scaling factors, the aim of the presented model is to provide erosion estimations within 15% of available empirical data, and to produce valuable data for different erosion mechanisms. The program allows for evaluation of all erosion mechanisms either combined or separately.

II. Channel Wall Erosion

When highly energetic ions impinge on the channel wall, they remove material from insulation that protects the circuit. So far, three erosion mechanisms are known, all related to ion bombardment: flow divergence as a result of the magnetic field topology, and particle scattering and sheath effect, which originate from the plasma behavior inside the channel.

A. Erosion Mechanisms

1. Sheath Effect

Through the boundaries, energy and particles enter and leave the system. Due to their low mass, electrons have a much higher thermal velocity than ions, and the electron flux to the boundaries of plasma exceeds the ion flux. Given this flux imbalance, the non-conductive channel wall acquires a negative charge, which repels electrons and accelerates ions such that the ion and electron flux at the wall becomes equal. This process thus generates a sheath, also called Langmuir sheath, with a negative potential φ_w that regulates the particle flux towards the walls and acts as a barrier to shield the plasma from the different conditions near the wall. The total potential in the sheath is equal to

$$\varphi_{tot} = \varphi_0 + \varphi_w = \varphi_0\left[1+\ln\left(\frac{m_i}{2\pi m_e}\right)-\ln(1-\sigma_e)]\right] \quad (1)$$

with φ_0 the pre-sheath potential, φ_w the potential drop in the sheath and σ_e the secondary electron emission (SEE). Parameters m_i and m_e represent the ion and electron mass, respectively. Ions enter the sheath with a minimum normal velocity called the Bohm velocity:

$$u_{Bohm} = \sqrt{\frac{kT_e}{m_i}} \quad (2)$$

with T_e the electron temperature and k the Boltzmann constant.

As the sheath is created to control the ion income at the wall, the generated potential is strongly related to the ion impacts due to remaining erosion mechanisms. A second important parameter is the re-emission of electrons into the plasma. From experiments, the SEE is found to be related to the plasma temperature, and conversely, the temperature depends on the number of re-emitted electrons. Combining a formula used by Yim[15] and data found by Raitses[8], yields the applied equation for the secondary electron emission:

$$\sigma_e = 0.70 + \left(\frac{1-0.70}{40}\right)\cdot T_e \quad (3)$$

From recent experiments performed by Gallimore and Hofer[10], large density gradients are measured at the plasma boundaries. These gradients shift the acceleration zone close to the wall further upstream, which results in a defocusing of the electric field. During test with a discharge voltage of 300 V, a radial electric field of about 50 V was established near the thruster's exit. This radial potential drop is very similar to the theoretical Langmuir sheath potential (eq. (1)) of about 70 V for the same operation conditions. So far, it is not clear to what extent the sheath effect and the electric field deviation due to density gradients are interconnected. Even when considering the observations as two separate phenomena, a radial electric field of the same strength is generated, attracting ions that impact the insulation. Therefore, either process can be simulated by introducing a general electric field which drives ions towards the wall. As the measurements are performed recently and the process is poorly understood, ion deviation due to a radially established field is allocated solely to the Langmuir sheath.

2. Particle Scattering

While being accelerated, ions encounter other particles before escaping the thruster. Although plasma is only slightly collisional, from time to time, ions are diverted from their path due to collisions with neutral atoms. After colliding, they might hit the channel wall thereby damaging the insulation.

The number of particles that are scattered, is determined by the collision cross-section σ_{in}. One unambiguous formula does not exist since the collision cross-section is derived from experimental data. However, a common characteristic is that the cross-section for collisions depends on the size of and the relative velocity between the two colliding particles. The adopted formula[6] (for xenon) for this model is

$$\sigma_{in} = 1.20 \cdot 10^{-18} - 1.96 \cdot 10^{-19} \cdot \log(u_{rel}) \qquad (4)$$

where u_{rel} is the relative velocity between the colliding particles. The coefficients in front of the exponentials stand for the atom size, and thus depend on the propellant.

3. Flow Divergence due to Magnetic Field

Flow divergence can arise from a misalignment of the magnetic field. The equipotential lines of the electric field tend to align themselves with the magnetic field lines, which causes the ion beam to diverge near the exit if the magnetic field has a defocusing effect. Deviating ions impinge on the wall and deface the insulation layer. However, it is apparent that the erosion originating directly from flow divergence is zero for properly designed magnetic circuits[3,15] (i.e. converging the ion flow inside the channel), which classifies flow divergence due to the magnetic field as a negligible erosion source.

B. Sputtering Yield

When impinging ions are sufficiently energetic, they remove one or more atoms from the channel wall. The sputtering yield depends on several factors, such as the impact angle, ion energy and insulation properties. The formula used to model the sputtering is a semi-empirical formula derived from experimental data and based on the theory of Yamamura and Tawara[14]. As Boron Nitride (BN) is the insulation material used for most SPT-100 experiments, formula derived from life tests is

$$S = \left(0.0099 + 6.04 \cdot 10^{-6} \gamma^2 - 4.75 \cdot 10^{-8} \gamma^3\right) \sqrt{E_i}\left(1 - \sqrt{\frac{E_{th}}{E_i}}\right)^{2.5} \qquad (5)$$

where γ is the impact angle (degrees) with respect to the normal to the wall, E_i the impact energy (eV) and E_{th} the threshold energy for sputtering (which is estimated[6] at 58 eV). The coefficients in front of the impact angle are typical for BN. Hence, if a different insulation is to be modeled, new coefficients have to be derived from experimental data.

III. Model Description

The simulation is based on a Particle-in-Cell (PIC) method. Particle motions are modeled in a 3-dimensional grid, whereas the erosion is modeled in 2-dimensional reference frame, as wall degradation is considered axisymmetrical[3,11,15]. The primary input consists of the 3-dimensional mesh grid, the magnetic field topology and the operation conditions. What follows, is a description of the program structure and the numerical methods that simulate the erosion processes.

A. Program structure

Figure 1 shows the flow diagram of the program. First, the initial operation conditions and thruster dimensions are set. From the selected input, plasma and electromagnetic properties are determined for every cell of the grid. Then, the simulation loops the different algorithms that model the erosion processes. One can distinguish clearly the aforementioned erosion mechanisms.

Although the program allows for separate simulation of each phenomenon, investigating each mechanism individually needs careful attention, because the processes erode the insulation simultaneously, and therefore influence each other. Furthermore, evaluating erosion due to the sheath, requires simulation of the other erosion mechanisms as well (see * in figure), because the sheath conditions depend on the incoming ions due to these processes. Even though flow divergence due to the magnetic field has been omitted as erosion source, the process is still incorporated in the program, in order to allow designers to investigate the influence of the magnetic field topology.

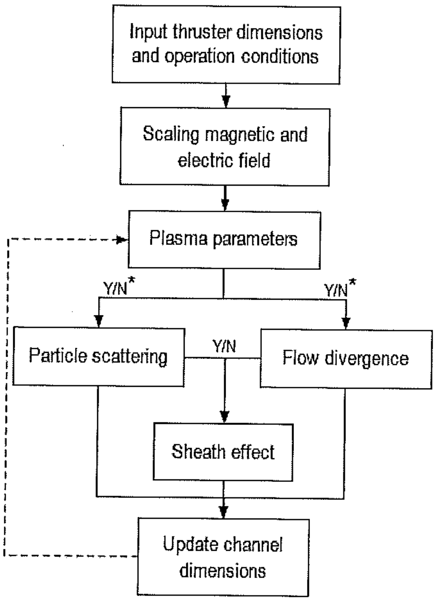

Figure 1: program flow diagram

After a given operation period, the thruster dimensions are updated and the plasma properties are recalculated. The electric and magnetic properties for each cell do not have to be rescaled after each update of the channel dimensions, because the shape of the magnetic field is not altered as the insulation materials in HETs have a relative magnetic permeability[11] of 1.

B. Physical Relations

The discharge is modeled assuming quasi-neutrality throughout the plasma. Electrons are treated as a fluid, whereas ions (and neutrals) are dealt with as discrete particles. In every axial section of the channel, the total and partial particle number densities are determined. This means that each type of ion in a certain section, i.e. having a mutual ionization position, is treated individually. Particle motions are simulated during an iteration time step *dt*, and averaged over a given period *T* in order to update the channel dimensions, and accordingly, the plasma properties.

To model the behavior of stationary quasi-neutral plasma along the discharge channel, a set of differential equations is used. The seven unknowns in the system are the ion number density n_i, neutral number density n_n, ion velocity u_i, neutral velocity u_n, electron velocity u_e, electron temperature T_e and electric potential φ. These parameters are all evaluated solely along the thruster's axis. When all plasma parameters are determined, ion scattering, flow divergence and the sheath effect are simulated.

The *continuity equations* only account for singly ionized particles. The effect of doubly ionized ions is not considered in the simulation.

$$\frac{d(An_iu_i)}{dx} = -\frac{d(An_nu_n)}{dx} = An_e\nu_i \qquad (6)$$

where A is the cross-sectional area and ν_i the ionization frequency (s^{-1}), which is defined by

$$\nu_i = n_n\sigma_i v_e \qquad (7)$$

with σ_i the ionization cross-section and v_e the electron thermal velocity.

Next, the *ion momentum equation* describes the forces influencing the ion motion.

$$m_iu_i\frac{du_i}{dx} = -q\frac{d\varphi}{dx} - \nu_i m_i(u_i - u_n) \qquad (8)$$

where $d\varphi/dx$ represents the electric field. The ionization process has no influence on the momentum of single ions (PIC method), and therefore, the ionization term can be omitted from the equation.

As electrons are modeled as a fluid, introducing the electrons in the model is achieved by setting the electron density equal to the ion density (quasi-neutrality) and replacing the momentum equation and energy conservation for electrons by experimental values for the electron temperature T_e. The corresponding thermal electron velocity

$$u_e = \sqrt{\frac{2kT_e}{m_e}} \qquad (9)$$

Further, it is assumed that the neutral velocity is constant, as they are not susceptible to electromagnetic forces.

$$\frac{du_n}{dx} = 0 \qquad (10)$$

Important to notice is that the magnetic field is not included in these fundamental equations, and yet, it is stated in the introduction that the magnetic field has an important influence on the motion of particles. In Hall thrusters, the magnetic field has no direct influence on ions due to their large Larmor radius. Consequently, ions only feel the magnetic field by its effect on electric field. On the other hand, electrons do feel the attraction of the magnetic field, but their motion is simplified by the introduction of experimental data. Therefore, the magnetic field is omitted from the fundamental equations that define the plasma, but directly implemented into the program.

IV. Erosion Model

Evaluating the fundamental equations for all sections individually yields a solution of the behaviour of all plasma parameters. From these parameters, the number of collisions N_{coll} is found, and successively, the number of free particles N_{free} (i.e. particles that will do not collide but follow their (diverging) path towards the exit).

A. Particle Scattering

The true number of collisions that occur in a period dt and over a distance dz is

$$N_{coll} = (n_i u_i A)\cdot(n_n \sigma_{in} dz)\cdot dt \tag{11}$$

in which the first factor is the ion number flow rate and the second factor the probability of an ion hitting a neutral over a distance dz. Once the number of collisions in each cell for each type of ion is known, the motion of the ions is simulated. The elastic ion-neutral collisions are modeled by a Monte Carlo method. The scattering direction of the colliding particles is represented by one random angle β, and a random collision coefficient α:

- α: determines the magnitude of the collision. Its value ranges from -1 to 1, where -1 indicates a head-on collision, and 1 signifies that the ion only grazes the neutral.
- β: indicates the scattering direction in the plane perpendicular to the thruster axis. Its value ranges from 0 to 2π.

The resulting ion velocity vectors are

$$\begin{aligned} u_{z,coll} &= 0.5(u_z + u_n) + 0.5(u_z - u_n)\cdot\alpha \\ u_{y,coll} &= 0.5(u_z - u_n)\left(1-\alpha^2\right)^{0.5}\sin(\beta) \\ u_{x,coll} &= 0.5(u_z - u_n)\left(1-\alpha^2\right)^{0.5}\cos(\beta) \end{aligned} \tag{12}$$

A number of colliding particles Y is simulated, and the eroded material volume in a time interval dt is

$$V_{erosion} = Sq\frac{I_{coll}}{Y} \tag{13}$$

B. Flow Divergence

The simulation of flow divergence is very similar to the simulation of ion scattering. The true number of free ions, i.e. the ions that do not collide with other particles, is the total number of ions minus the colliding ions.

$$N_{free} = (n_i A dz) - N_{coll} \tag{14}$$

A number of free particles K is simulated, and the eroded material volume in a time interval dt is

$$V_{erosion} = Sq\frac{I_{free}}{K} \tag{15}$$

C. Sheath Effect

For each position along the channel wall, the sheath potential that is required to balance the ion and electron flux, is calculated with

$$\varphi_w = \frac{kT_e}{q}\ln\left[\left(\frac{\Gamma_{i,FD}+\Gamma_{i,PS}}{\sqrt{\frac{kT_e}{2\pi m_e}}(1-\sigma_e)}\right)+\sqrt{\frac{2\pi m_e}{m_i}}\frac{1}{(1-\sigma_e)}\right] \tag{16}$$

Next, it is computed what the corresponding electron flux Γ_e ($m^{-2}s^{-1}$) is towards the walls:

$$\Gamma_e = 0.5 n_e \cdot \exp\left(\frac{q\varphi_w}{kT_e}\right)\sqrt{\frac{kT_e}{2\pi m_e}}(1-\sigma_e) \tag{17}$$

The total ion flux to the walls must coincide with the net total electron flux. The number of ions attracted by the sheath (per second) is therefore

$$N_{SE} = S_z\Gamma_e - \left[\frac{\left(\frac{I_{coll}}{Y}N_{coll}\right)+\left(\frac{I_{free}}{K}N_{free}\right)}{dt}\right] \tag{18}$$

where S_z is the surface area of the individual axial sections, I_{coll} and I_{free} are the number of simulated wall impacts due to particle scattering and flow divergence, respectively.

Ions that are not diverted towards the wall due to scattering or flow divergence enter the sheath with the Bohm velocity (eq. (2)) in normal direction, while their tangent velocity is determined by the applied electric field. Once they enter the sheath, they are further accelerated by the negative sheath potential. If the impact energy is adequate, the eroded volume per second is

$$V_{erosion} = Sq\frac{N_{SE}}{Q} \qquad (19)$$

where S is the sputtering yield, N_{SE} the number of particles entering the sheath, and Q the number of simulated particles.

V. Results

Figure 2 shows the simulated erosion of the outer channel BN insulation for different firing periods with an SPT-100[2,12], operating with xenon. Measurements performed by Absalamov[1] are added to the graphs to ease the discussion and the validation of the model.

The contribution of the individual erosion mechanisms is demonstrated by the erosion rate graphs in fig. 4. As flow divergence does not occur for a focusing magnetic field, only the effect of particle sputtering and the sheath are plotted. Comparing the individual rates to the total erosion rate, it is apparent that the sheath effect has a great impact on the erosion process.

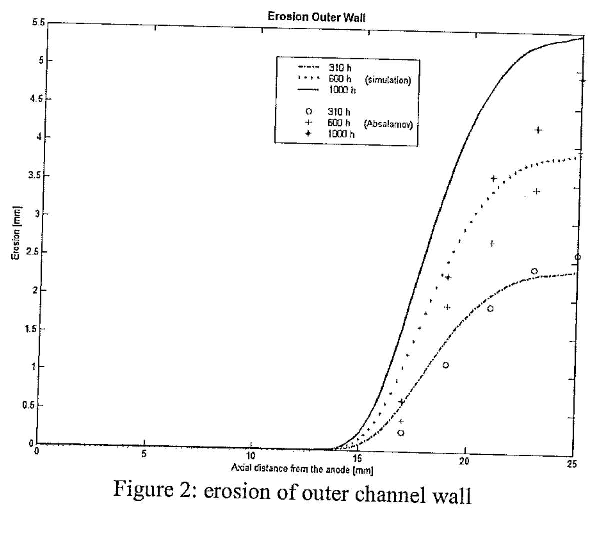

Figure 2: erosion of outer channel wall

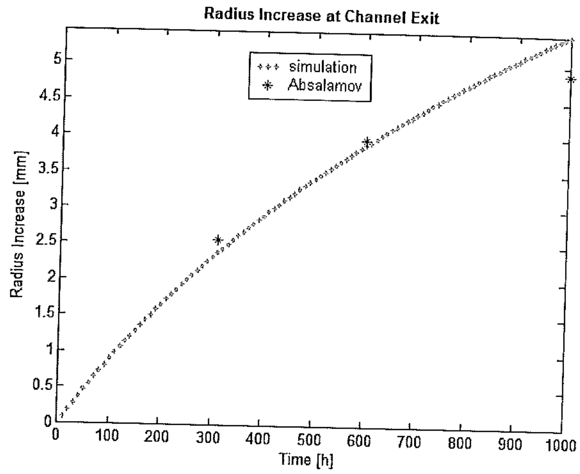

Figure 3: increase of the outer radius at the exit plane

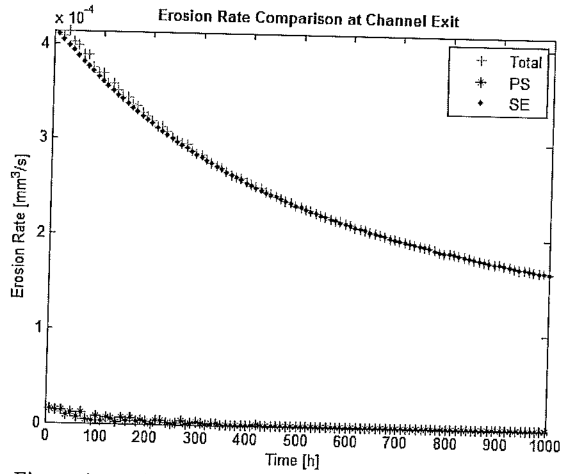

Figure 4: erosion rate for Particle Scattering and Sheath Effect versus total erosion rate, outer channel wall

VI. Discussion

Both from literature and obtained model results, flow divergence as a result of a misaligned magnetic field was discarded from the erosion processes in Hall thrusters. The contribution of ion scattering amounts to barely 5%, and hence, the dominant source of wall deterioration is found in the interaction of the plasma with the wall.

Figure 4 demonstrates the significance of the sheath effect. Especially after 300 hours of operation, ion scattering almost disappears as erosion source, and the sheath conditions take over completely.

Figure 2 indicates the saturation of the erosion rate, which can be directly linked to channel widening. The velocity parallel to the wall, which is acquired by the applied electric field, lowers when the angle of the channel wall increases, and consequently, diminishes the impact energy as time proceeds. A second reason for decreasing erosion rates is the plasma density which becomes gradually lower with an increasing channel radius.

The erosion graphs in fig. 2 and 3 are in fair agreement with experimental values for the first 600 hours of operation, but after this period, overestimation is observed. Comparing with the empirical data obtained by Absalamov[1], the overestimation of the maximum erosion is as high as 10%. In addition, the erosion onset is shifted towards the anode.

With the sheath effect as the dominant source of erosion, different reasons can explain the overestimation. With the secondary electron emission defined as a function of the temperature[13,15], its value remains constant because the temperature distribution is held constant in the model. Further, according to Keidar and Boyd[5], the temperature distribution varies with a change of the SEE coefficient. Temperature variations influence the electron flux to the wall and the ionization process, and therefore the erosion of the channel wall. Furthermore, the electron flux to the wall can alter because of sputtered insulation material forming a lose layer on the channel wall, or by backsputtered material from the walls of the vacuum chamber. Last, variation of the surface structure and electron bombardment[13] can increase the electron emission or lower the sputtering yield, thereby reducing erosion.

However, comparing theoretical results with experimental data is not straightforward, as many variables such as the collision cross-section, ionization cross-section and the sputtering yield are all characterized by a statistical approach; any deviation from the real values affects the erosion prediction. Additional experiments are required to perform full validation of the results, and to improve the model.

VII. Conclusion and Recommendations

The presented model in this work forms a solid basis for the simulation of erosion in Hall Effect Thrusters. It provides valuable information on how wall erosion originates. As ion collisions cause little erosion and flow divergence does not occur for properly designed magnetic circuits, wall conditions have proved to be the dominant cause of channel erosion, which has also been observed by recent experiments, and different theoretical models.

The simulation outcome shows a similar trend as obtained from experiments[1], and the erosion estimation is within 15% of the measured values, which was set as the goal accuracy for the erosion prediction. The difference with empirical data becomes more significant with increasing firing time. Different reasons clarify this behavior.

First, during life tests, the electron flux to the wall can alter due to interaction of the plasma with the environment. Next, during operation, the surface properties vary and thereby influencing the erosion rate. This effect is not simulated by the model.

Study of the literature reveals little on the behavior of plasma near a solid surface. Recent experiments[10] show potential drops near the wall, in radial direction. The developed model attributes this radial electric field completely to the sheath conditions. However, the source of the generated electric field needs a thorough investigation because it seems closely related to the sheath effect as it is known to this day.

Research on the approximation of plasma parameters, and the properties of insulation materials and propellant, will lead to a more detailed characterization of the plasma. Moreover, thorough investigation of the wall conditions and its interaction with plasma is needed to further develop the program and to provide a more accurate prediction of the lifetime of Hall Effect Thrusters.

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