The Effect of Wall Erosion on the Performance of Hall Thrusters

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Abstract: Long-term operation of Hall effect thrusters is accompanied by change in its performance. A set of life tests conducted in Keldysh Research Centre showed monotone decrease of thrust efficiency and specific impulse during the initial 500-1000 hours of operation. The role of discharge channel geometry change in observed phenomenon is investigated. On the base of zero-dimensional model a quantitative relation between propellant utilization efficiency and channel geometry is obtained. It allows semi-empirical prediction of the anode specific impulse change during long-term operation. The relation is validated using results of life tests of four Hall effect thrusters with nominal power range from 200W to 1.5 kW.

Nomenclature

e	=	elementary charge
g	=	free fall acceleration
h	=	discharge channel height
I_{spa}	=	anode specific impulse
J_d	=	discharge current
J_i	=	ion current
j_i	=	ion current density
L	=	discharge channel length
L_A	=	acceleration region length
L_I	=	ionization region length
M	=	ion mass
$\dot{m}_a$	=	anode propellant mass flow rate
$\dot{m}_i$	=	ion mass flow rate
$\dot{m}_w$	=	ion mass flow rate to channel walls
N_d	=	discharge power
n_e	=	electron number density

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n_i	=	ion number density
P_r	=	probability that atom, emitted by channel wall, returns to the ionization region
R	=	thrust
S_c	=	cross section area of discharge channel
V_a	=	thermal velocity of atom
β_i	=	averaged product of ionization cross-section by electron velocity
η_a	=	anode thrust efficiency
η_J	=	electron current utilization efficiency
η_m	=	propellant utilization efficiency
η_U	=	thrust loss caused by ion angular and energy distributions
λ_i	=	mean free-path of ionization
$\Delta\varphi_I$	=	potential drop in ionization region

I.   Introduction

Hall effect thruster (HET) lifetime is limited mainly by erosion of discharge channel walls occurring because of ion bombardment. The erosion leads to thinning of the walls near the channel exit up to its full destruction, after which the sputtering of the magnetic pole pieces begins. Sometimes this moment is considered as a lifetime limit criterion, although life test of SPT-100 showed ability of efficient long-term thruster operation even after beginning of the magnetic system erosion[1]. Sometimes HET developers use another criterion to fix the life limit. In the course of long operation the lowering of efficiency parameters may take place[2,3]. Therefore the life limit may be defined as a point of time when the thruster performance characteristics run out of acceptable bounds. These bounds for efficiency and specific impulse can usually be calculated from requirements of specific ballistic task.

Until now two possible reasons of HET performance worsening during long term operation were considered. First is deposition of the films formed by sputtered ceramic material on the anode and discharge chamber walls[4]. The films influence on the nature of plasma interaction with walls, in particular change the near anode potential drop. Besides from time to time film flaking occurs accompanied by unstable operation, increased discharge current and thermal loss. If in the course of life test films are periodically removed, some temporary performance enhancement is observed, but the efficiency of cleaned thruster remains lower than at the beginning of life test. Therefore the films deposition is not the only reason of the efficiency and specific impulse decrease.

The second reason is alteration of the plasma properties due to change of the geometry of discharge channel walls. The usual explanation is that the erosion results in growing of the channel cross-section, reduction of the plasma density and volume ionization rate; however any quantitative estimations of this effect were not published. This explanation seems not enough convincing, as the most noticeable geometry change occurs near the exit of the channel where the ionization rate is relatively small and mainly the acceleration of the ions takes place[5]. According to probe data the ionization region is located closer to anode where the channel cross-section increase is relatively small.

In this paper we consider a process that is probably the main reason for the observed performance reduction.

II.   Typical behavior of HET efficiency factors

The main factors describing performance of HET anode unit are the anode thrust efficiency

$$\eta_a = R^2 / 2\dot{m}_a N_d \tag{1}$$

and anode specific impulse

$$I_{spa} = R / \dot{m}_a g , \tag{2}$$

where R – thrust; $\dot{m}_a$ – anode mass flow rate, N_d – discharge power; g – free fall acceleration.

It is useful to factorize these values to distinguish different kinds of loss[5]. Propellant loss because of not full ionization is characterized by propellant utilization efficiency

$$\eta_m = \dot{m}_i / \dot{m}_a \, , \qquad (3)$$

where $\dot{m}_i$ – mass flow rate of ions in plasma plume. The ratio

$$\eta_J = J_i / J_d \, , \qquad (4)$$

where J_i – ion current; J_d – discharge current, characterizes electron current utilization efficiency. Thrust loss caused by ion angular and energy distributions is characterized by factor

$$\eta_U = R / R_{id} \, , \qquad (5)$$

where R_{id} is an ideal thrust, which could be achieved if all ions run parallel to the axis and have the same energy corresponded to discharge voltage. Neglecting double and multiply charged ions the anode efficiency and specific impulse may be written as

$$\eta_a = \eta_m \eta_J \eta_U^2 \, , \qquad (6)$$

$$I_{spa} = \eta_m \eta_U \sqrt{2eU_d / Mg^2} \, , \qquad (7)$$

where e – elementary charge and M – mass of ion.

During the life tests curried out in Keldysh Center at different times a monotone decrease of both η_a and I_{spa} was usually observed. In the course of these tests periodical measurements of angular and energy distributions of ions in plasma plume were carried out, and factors η_m, η_J, η_U were calculated using method described in Ref. 6. As it turned out, after the first 500-1000 hours of thruster operation the factor η_U remains practically unchanged, the value of η_J decreases on 3-5% and the propellant utilization efficiency η_m is subjected to the strongest reduction – up to 10%. Typical behavior of these factors during life test is demonstrated in Fig.1. It is seen that reduction of η_m is in fact the only reason of the anode specific impulse reduction and the most valuable reason of the efficiency change. Therefore in the remainder of this paper we will concentrate on the propellant utilization efficiency.
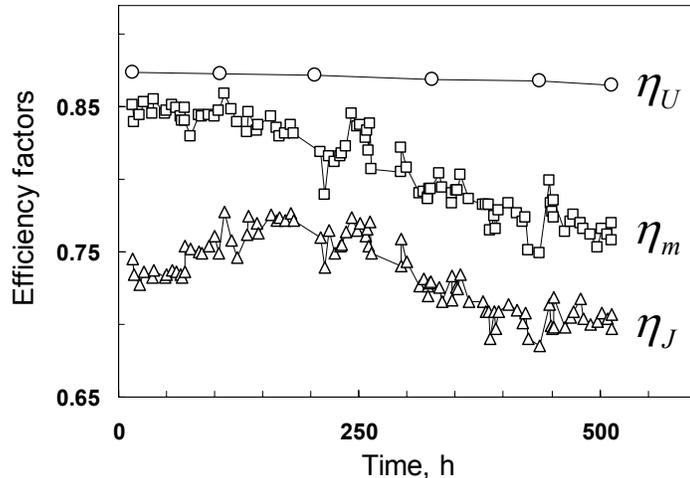

Figure 1. Typical efficiency factors behavior during life test.

III.   Estimation of propellant utilization efficiency

The main parameter determining the propellant utilization efficiency is a mean free-path of neutral atom ionization

$$\lambda_i = V_a / \beta_i n_e , \tag{8}$$

where V_a – typical thermal velocity of atom, n_e – typical electron number density in the ionization region, $\beta_i \equiv \langle \sigma_i \upsilon_e \rangle$ – product of ionization cross-section by electron velocity averaged over the electron distribution function. The ratio λ_i / L, where L is the channel length, was accepted as a similarity parameter for discharges in Hall thrusters[7], and inequality

$$\lambda_i / L \ll 1 , \tag{9}$$

is usually referred to as one of the main necessary condition of efficient thruster operation[5].

Practical application of this inequality is a problem as real length of ionization region is not equal to the discharge channel length. Experience of thrusters testing shows that L does not influence on thruster performance on conditions that this length is greater than both channel height h and typical scale of magnetic field variation. Therefore on derivation of formula for η_m we have to introduce some conditional length of ionization region L_I. It was stated in Ref. 8 that for estimations one can assume approximate relation $L_I \sim h$, which is reasonable due to peculiarity of magnetic field configuration in traditional HET design. Actually, this conclusion was a recognition of observable in experiments and confirmed by results of numerical modelling regularity, consisting that ionization region characteristic size is defined by magnetic field distribution. The ionization area is located in the region with the fastest reduction of magnetic field in a direction from the thruster exit to the anode[9]. Numerical calculations show, that in usual HET design, having screens intended to increase magnetic field gradient, the characteristic scale of magnetic field variation is of the order of gap between screens and it is close to channel height. As a result we obtain relation $L_I \sim h$. Nevertheless this relation can not be used in estimation of ionization efficiency variation due to channel height increase. Most probably L_I will not be changed if the magnetic field remains constant, of course on conditions that the discharge power and discharge voltage are also constant.

If not take into account ions loss on the channel walls the propellant utilization efficiency may be expressed as probability of neutral atom ionization when it crosses the plasma region with length L_I:

$$\eta_m = 1 - \exp\left(- L_I \beta_i n_e / V_a\right). \tag{10}$$

To estimate typical value of electron density it is possible to use quasi-neutrality condition $n_e \approx n_i$ and write the ions density as a ratio of ion current density j_i to elementary charge and velocity gained by ions in the ionization region with potential difference $\Delta\varphi_I$:

$$n_i \approx j_i / (e V_i) \approx (j_i / e)\sqrt{M / (2e\Delta\varphi_I)} . \tag{11}$$

The propellant utilization efficiency by definition equals ion flow divided by propellant atoms flow. If use flow densities instead of flows it is possible to write

$$j_i = \eta_m \left(e\dot{m}_a\right) / (M S_c), \tag{12}$$

where S_c – channel cross-section in the ionization region. Using (10)-(12) the following equation can be obtained

$$\eta_m = 1 - \exp(-\gamma \dot{m}_a \eta_m), \tag{13}$$

where

$$\gamma = \beta_i L_I \Big/ \left(V_a S_c \sqrt{2eM\Delta\varphi_I} \right). \tag{14}$$

It can be shown that numerical solution of this equation is well enough approximated by expression

$$\eta_m \cong 1 - \exp[-1.5 \cdot (\gamma m_a - 1)], \tag{15}$$

and relative error of approximation in practically important range of $\eta_m > 0.8$ is less than 1%.

It is seen that if $\dot{m}_a = const$ the only parameter γ can be responsible for decreasing of η_m. But the appearance of expression (14) does not give a key to understanding the reasons of performance degradation. Indeed, as it was discussed, in all likelihood the length L_I mainly depends on the magnetic field and does not dramatically change during long term thruster operation. The bulk ionization rate β_i is a functional of the electron velocity distribution function and roughly depends only on the electron temperature, which in turn is a function of discharge voltage[10]. As it was already mentioned, the channel cross section S_c undergoes noticeable change not in the ionization region but mainly in the acceleration region. The thermal atoms velocity V_a should be unchanged in case of stable thruster operation. It is also difficult to find reasons for $\Delta\varphi_I$ change if propellant flow rate, discharge voltage, magnetic field and channel height in the ionization region are constant values. So, it is possible the make a reasonable assumption, that during long term operation $\gamma \sim const$, and therefore we have to take into account the ions flow to the channel walls.

It would be possible to introduce in consideration the effective ionization length that is shorter than L_I, especially as because concept "the length of ionization region" has conditional character at continuous plasma parameters distribution. However reduction of ion current is not the only consequence of ions loss on the walls. Having collided with the walls, ions recombine, forme neutral atoms, come back to discharge channel and can be ionized again. Probe measurements show, that the ion current density on the channel walls is very high and comparable with ion current density in the discharge channel. For example the near-wall probe measurements inside discharge channel of the HET PPS-1350 operating in nominal mode with power 1500 W, showed[12] the maximum ion current density to the external wall as high as 40 mA/cm² whereas the equivalent propellant current density was approximately 70 mA/cm². It was also noted in the Ref. 12 that the total ion current to external wall was ~45 % of current equivalent to the mass flow rate through the discharge channel. Consequently the channel walls can be considered as intensive "sources" of neutral atoms comparable by intensity with anode-gas distributor and for accurate estimation of η_m it is necessary to take into account the wall "sources" by adding their flow rates to $\dot{m}_a$ (Fig. 2).

It is important to note, that typical distributions of ion current density along the wall measured in the Ref. 12, were non-uniform and had a maximum located near the channel exit approximately in the same place where the basic plasma potential fall was registered and where walls erosion is usually observed, i.e. there is a change of the channel geometry. Taking into account, that at change of the walls shape the average direction of the emitted flow also changes, it is possible to suppose the following mechanism of η_m reduction. The neutral
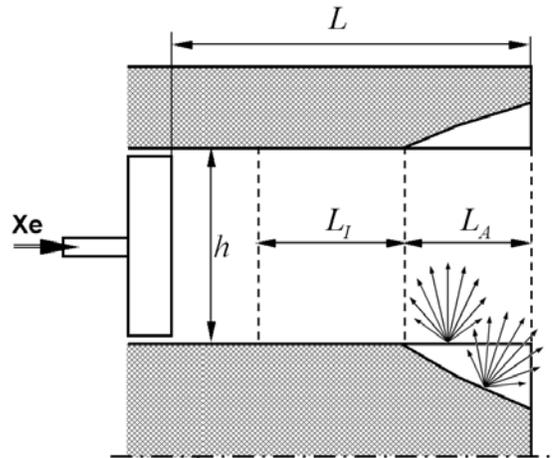

Figure 2. Diagram of discharge channel with wall "sources" of neutral atoms.

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atom velocities at diffuse reflection are distributed symmetrically with respect to a surface normal. At the initial stage the channel walls have a cylindrical form and probability for atoms to be emitted in a direction of the anode and to be repeatedly ionized is close to probability to be emitted in a direction of the channel exit and to leave the thruster as neutral atom. As a result of sputtering the walls get an inclination aside the channel exit. Thus the probability that emitted neutral atom will move in a direction of the anode decreases and neutral atoms flow leaving the thruster is increased, i.e. the propellant utilization efficiency is reduced.

To take into account influence of the walls shape on η_m the additional mass flow rate from the walls could be written as $\dot{m}_w P_r$, where $\dot{m}_w$ – mass flow rate of ions to channel walls in region where erosion takes place, P_r – averaged over this region probability, that the atom emitted from the wall, will move in a direction of the anode. Substituting this additional mass flow rate to (15) one can obtain a formula expressing dependence of propellant utilization efficiency on the channel geometry

$$\eta_m \cong 1 - \exp\left\{-1.5 \cdot \left[\gamma\left(\dot{m}_a + \dot{m}_w P_r\right) - 1\right]\right\}. \tag{16}$$

Consider whether this mechanism explains the observed reduction of thruster performance.

IV.   Approach to the model verification

At different times a number of life tests were carried out in Keldysh Research center. During all of these tests measurements of ion angular and energy distributions in plasma plume were periodically made and propellant utilization efficiency were calculated. Also measurements of the channel walls shape were curried out approximately once a 100 hours to estimate erosion rate and predict thruster lifetime. These results were used to calculate probability P_r.

The calculation procedure included numerical simulations of neutral gas flow inside discharge channel in free-molecular regime. The simulation area was bounded by surfaces of walls in radial direction, and by planes perpendicular to axis of thruster enclosed zone where sputtering of walls took place (area with length L_A in Fig. 2) in axial direction. Domain boundaries associated with channel walls were divided into set of nodes. Each of these nodes step by step was set as a source of neutral atoms with Maxwell velocity distribution and calculation of gas flow was performed. On the walls diffuse law of reflection was assumed. Planes perpendicular to the thruster axis are considered as transparent boundaries. For each node position the probability for atom to return to ionization region was calculated as ratio of the flow effluent from simulation domain in the anode direction to the total inward flow. The final value of probability P_r was calculated by averaging of these local probabilities over all nodes on the domain boundaries associated with channel walls.

It is to be noted, that in HET with conventional design the channel height is usually more, than the length of area in which wall erosion takes place. Therefore a few number of repeated reflections from walls occurred before atom leaves simulation area. Simulations showed, that without appreciable loss of accuracy one can calculate the probability for atom to return to ionization area as a probability to be emitted with initial speed having axial velocity component directed aside the anode. It is easy to see that, at diffuse law of emission this probability is determined by expression $(1 - \sin\alpha)/2$, where α is an angle between tangent to the wall and thruster axis.

So, if η_m and $\dot{m}_a$ can be measured and P_r can be calculated, there are two unknown values γ and $\dot{m}_w$ in Eq. (16). It is unlikely possible to make reliable quantitative assessments of these values, but one can suppose they weakly change during long term operation. As it was discussed above, condition $\gamma \approx const$ is a reasonable assumption. It is rather difficult to estimate how much the flow of ions to the wall changes. Authors do not know any studies devoted to this question. Therefore, we will assume $\dot{m}_w \approx const$ and the extent to which the experimental and calculated data agree to each other will serve as an indirect confirmation or refutation of the correctness of the made assumption.

Assuming that P_r is the only quantity determining reduction of thruster performance, from (16) one can find parameters γ and $\dot{m}_w$ using values η_m, $\dot{m}_a$, and P_r measured at two different moments of time:

$$\gamma = Q_1 \frac{P_{r1}Q_2 - P_{r2}Q_1}{m_{a2}P_{r1} - m_{a1}P_{r2}}, \quad m_w = \frac{m_{a2}Q_1 - m_{a1}Q_2}{P_{r1}Q_2 - P_{r2}Q_1}. \tag{17}$$

Here the integers denote the number of measurement and for brevity the notation $Q = 1 - (2/3)\ln(1 - \eta_m)$ is introduced. Using walls profiles data at subsequent points of time, it is possible to calculate the propellant utilization efficiency and to compare them with measured values. The next section describes the results of this analysis.

V. Experimental results

Analysis of life tests results was conducted for four thrusters: KM-32, KM-60B, KM-60N, and KM-88, differing in power, voltage and wall materials of the discharge channel. The propellant in all experiments was xenon.

Low power thruster KM-32[2] with the discharge channel, made of ceramic BN-05, which is a composite of boron nitride (90%) and boron oxide (10%), was tested at discharge voltage of 250 V and discharge power of 200 W for 500 hours. Two modifications of the HET series KM-60 were tested at discharge voltage of 500 V and discharge power of 900 W. The first modification KM-60B, in which the discharge channel was made of ceramic BGP-10 (composition of 60% boron nitride and 40% silica), was tested for 500 hours, the second – KM-60N with ceramics BN-05 was tested for 1000 hours. Thruster KM-88[11] with ceramics BGP-10 passed 500 hours of life test at discharge voltage of 550 V and discharge power of 1600 W. In conducting the tests the discharge voltage and current levels maintained constant. The constancy of the discharge current was provided by propellant mass flow rate control. Results of the comparison of calculated and measured values of I_{spa} are shown in Fig. 3.
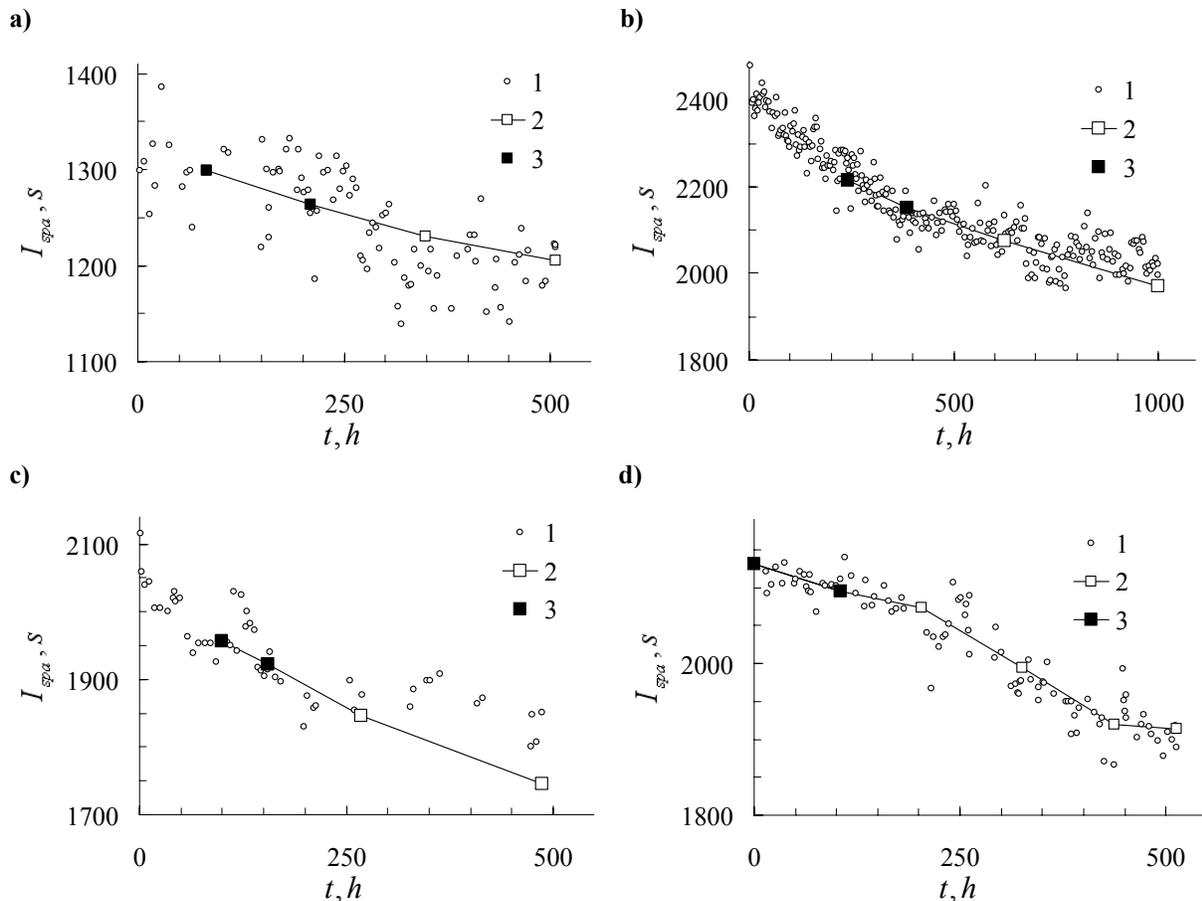

Figure 3. Anode specific impulse of HET КМ-32 (a), КМ-88 (b), КМ-60B (c) and КМ-60N (d) as a function of time: 1 – experimental points; 2 – calculated values; 3 – points used for calculation of γ и $\dot{m}_w$.

In three of the four presented test series the current in the magnetic coils had to be changed. This is due to the observation that the optimal thruster operation with the highest values of efficiency and specific impulse at the initial stage of life tests was achieved with a stronger magnetic field. As sputtering changes shape of the walls the mode of thruster operation also changes, sometimes discharge becomes unstable. The most probable reason for this behavior is increase of the mirror ratio of the magnetic field, due to the expansion of the channel, and the difficulty of electron transport. In this case it is possible to ensure stable operation of the thruster by some reduction of current in magnetic coils. Usually, this leads to some changes of performance parameters, which are not directly related to the studied processes. As it was noted above, the adjustment of the magnetic field can lead to change in position and length of the ionization region, so all results presented in Fig. 3, were made for those periods of tests, when the magnetic field was kept constant.

To calculate the parameters γ and $\dot{m}_w$ using expressions (17) the first two points in time of the period in which the magnetic field remained constant were taken. Calculations showed that for three of four engines (except for KM-88) calculated ratio $\dot{m}_w/\dot{m}_a$ was in the range 1.0-1.5. For the thruster KM-88 this ratio was approximately 3.8. These values are consistent with the results of near-wall probe measurements[12], according to which the ion current on the external wall was about half of the equivalent current corresponding to mass flow rate $\dot{m}_a$. Recall that in Eq. (16) the value m_w is the total flux of ions both to external and internal walls. The increased ion flow to the walls obtained for the HET KM-88 may be either inherent feature of the thruster or result of low precision of calculations. For this thruster there were changes in the magnetic field up to 200 hours. As a result of sputtering processes slowdown on this stage of operation the members of differences in expressions (17) become close to each other and this leads to less accurate calculations.

It is seen that the measured values of the anode specific impulse are close to estimations. One can therefore conclude that considered mechanism is most likely a major determining overall decrease of HET performance. It also serves as an indirect confirmation of the assumptions made about the relatively weak variation of the parameters γ и m_w at least in the beginning period of 500-1000 hours of operation.

VI.   Conclusion

The quantitative relation between the discharge channel geometry and propellant utilization efficiency is obtained. It allows calculating the anode specific impulse reduction occurring when changing the form of the walls as a result of ion sputtering. The essence of the phenomenon lies in the fact that the change in the shape of the channel walls leads to an increase in the proportion of neutral atoms, leaving the discharge region without re-ionization. Comparison of theoretical and experimental data shows a good agreement, which suggests that this mechanism is probably one of the main responsible for the decrease of the output HET characteristics. If so, it is possible to predict variation of specific impulse for long time period, based on the results of shortened life tests. As it was shown[13], availability of walls shape measurements at several points of time at the initial stage of operation enables prediction of the subsequent erosion for the period up to five times longer. Calculating probabilities P_r for predicted wall shapes it is possible to predict also η_m and assuming $\gamma \approx const$ and $\dot{m}_w \approx const$ obtain forecast of the dynamics of I_{spa} change. Besides, assuming $P_r = 0$ it is possible to estimate the limiting minimum value to which the I_{spa} may fall.

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