The Wear of the Channel Walls in Hall Thrusters

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The activities on forecasting of lifetime of ACD (accelerators with closed electron drift) are conducted rather for a long time. But many problems are far from being solved while. The main reason of this is that the lifetime of the Hall thrusters reaches several thousand hours. Such big lifetime hampers the direct experimental study of influence of accelerators parameters on a wear of channel walls.

It is well known, that among the different reasons limiting the lifetime of thrusters such as ACD, the most critical is the wear of the walls of the acceleration channel. The wear of the walls happens owing to the interaction of the accelerated ions flow with channel walls (ionic sputtering). Obviously the research of this process and, as a consequence, the knowledge of the model of the channel walls wear depending on the various factors would allow to make to a high precision the evaluations of lifetime, and also could form the basis for the development of a technique for accelerated tests of ACD.

Now for forecasting of the ACD lifetime they usually use various empirical relations. In the given paper the attempt of theoretical research of the main processes influencing to the wear of the acceleration channel walls and, hence, on lifetime of ACD in whole was made. It was shown, that the greatest substantiation from the now in use formulas for prediction of lifetime has the logarithmic relation from time. The simple analytical expressions are obtained for an evaluation of empirical factors used in this logarithmic relation, through the parameters of the accelerator. These results enable us the opportunity to estimate and to predict the degree of the wear of channel walls beforehand, at stage of designing, depending from the operation mode of ACD and its duration.

The data obtained during the life test of stationary plasma Hall thruster are presented as an experimental confirmation of the method of lifetime estimation submitted. The results of forecasting of the erosion rate and of thruster lifetime are given. The evaluation of accuracy of the forecasts, gotten with use of logarithmic formula, depending on thruster operation time and forecast period is performed.

Introduction

Among a number of the reasons limiting a resource of the plasma Hall type thrusters, the most critical is the wear of the acceleration channel walls. It occurs owing to interaction of the flow of the accelerated ions with the walls (ion's dispersion). It is obvious, that research of this process and, as a consequence, knowledge of the model of the wear of walls depending on the various factors, would allow to make exacter the thrusters life time estimations, and also could form the basis for development of a technique of the accelerated tests of thrusters.

In spite of the fact that the works devoted to the determination and forecasting of the lifetime of Hall thrusters are conducted rather for a long time, many problems are not solved while. The reason is that the lifetime of the Hall thrusters achieves several thousand hours, and this fact complicates experimental researches of the channel walls wear which depending on the large number of various factors. And the theoretical researches are

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complicated by complexity of the description of the formation of ions flow in the channel and its interaction with the walls. Therefore in the given situation most productive is the combination of experimental and theoretical development.
In the given work the substantiation of logarithmic dependence (21) of the wall wear from an operating time of the thruster is carried out by physical modeling of the plasma flow in the channel.

Ion dispersion of the wall of the channel

Let's consider process of dispersion of edge of a wall of isolator in the exit from the channel of acceleration (see fig.1). Volume of the sprayed substance W is equal

$$W = \frac{Sdy}{2}\cos\Theta \qquad (1)$$

Where Θ – the angle of a deviation of the wall surface owing to wear from an initial direction; dy – the size of the wall wear; S – the area of the wear surface.

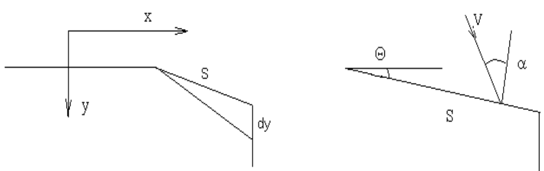

Fig.1. The dispersion of the acceleration channel wall.
Then the number of the sprayed particles is equal

$$N_w = \frac{W\rho}{M_w} \qquad (2)$$

Where ρ – the density of the wall material; M_w - weight of atom of sprayed substance.
The Factor of dispersion we shall define as follows

$$S_w = \frac{N_w}{N}, \qquad (3)$$

where N – the number of particles, which make the dispersion. It is obvious, that

$$N = nVS\cos\alpha\, dt \qquad (4)$$

where α - the angle of fall of ions on the wall; V – the average velocity of ions near the wall; n – the density of ions near the wall.
In view of the previous expressions we have the following formula for the velocity of the wall wear

$$\frac{dy}{dt} = \left[\frac{M_w}{\rho}S_w\right] nV\frac{2\cos\alpha}{\cos\Theta} \qquad (5)$$

For our further purposes it is useful still to enter the angle γ between the axis x and the vector of the average flow velocity V near the wall. In other words, it is the angle of the deviation of the average flow velocity near the wall from the direction of the average velocity for all jet as a whole. Usually axis x is directed along a wall (fig. 1), and then the angle γ is expressed through the already entered angles α and Θ as follows

$$\gamma = \pi/2 + \Theta - \alpha \qquad (6)$$

With the account (6) the expression for the wall wear (5) after transformations passes in

$$\frac{dy}{dt} = \left[\frac{M_w}{\rho}S_w\right] nV(2\sin\gamma)\left(1 - \frac{tg\Theta}{tg\gamma}\right) \qquad (7)$$

Let's note, that in our statement of a task it is supposed, that $\gamma > \Theta$, differently, of course, the dispersion will be stopped.

The factor of dispersion of a surface

The factor of a surface dispersion S_w may be expressed as the product of the two multiplicands, one of which depends only on ions energy $\varepsilon = MV^2/2$, another from the angle of the fall α:

$$S_w(\alpha, \varepsilon) = S_\varepsilon S_\alpha \qquad (8)$$

The experimental dependences S_ε on energy and S_α from the angle of fall are received for various materials of walls of the channel of the accelerator (see, for example, [1]). Usually S_ε for the given material accrues almost linearly from energy of falling particles, i.e. $S_\varepsilon = k_\varepsilon \varepsilon$, where k_ε -is the constant value for the given material. The value S_α is accepted to equal 1 at α = 0 (the fall of particles is normal to the surface), then, in process of increase of the angle α S_α is increased monotonously and reaches a maximum in the region of angles α = (50°-60°), then approximately linearly falls down to 0 at α→ 90°. The value of a maximum for metals is near S_α = 2, and for ceramics can reach values S_α = 3÷4.
For the researched task the ion flow along the walls of the channel is characteristic, therefore, apparently, angles of fall should be close to 90°. However, it is impotent to take into account such specific feature of the accelerator of plasma as the presence of the near wall potential. For ions this potential results in their additional acceleration in the direction of the wall, that is the reduction of the angle of fall α. As the estimations show, the value of the near wall potential in the zone of acceleration is 2÷3 times more than the electron kinetic energy in the direction of the magnetic field T_{II} (it is known, that the distribution of the electron energy in the channel is anisotropic, i.e. $T_{II} < T_\perp$). And this energy T_{II}

monotonously accrues from small value ~ 2 eV (the electron temperature in the area of the cathode or at the end of the acceleration zone) up to value of the order $0,5\cdot\varepsilon_1$ in the beginning of a layer of acceleration, where ε_1 – the threshold power of the electron duplication for the material of the wall in the secondary electronic emission processes.

For example, in the region of channel exit edges of the thruster T-100 [2], which walls are made of a material on a basis of BN (boric nitride), the near wall potential value can reach ~ 40 eV, and the average energy of ions is about the half of the enclosed discharge voltage U ~ 300 B. Then even if the flow of ions goes almost parallel to the wall surfaces, the near wall potential before the collision of an ion with the wall will change the angle of fall from ~ 90° up to ~ 60°, and essentially increase the value of S_α .

Thus, the real angle of fall α^* for substitution in S_α needs to be calculated with the account of the near wall potential, i.e. $\alpha^* = \alpha - \alpha_w$, where α_w is determined through the ratio of the near wall potential φ_w to the energy of ions.

The total flow of ions on walls

The estimation from above of the total ions flow I_w on the walls of the acceleration channel can be made, if one subtract from the complete jet pulse its real measured in experiments part. Theoretically achievable (complete) jet pulse F_t, provided that the velocity of all ions is directed along thruster axis, is equal

$$F_t = GV_U = M\int < nV > dS\sqrt{\frac{2eU}{M}} \qquad (9)$$

Where G – the flow rate, U – the discharge voltage, M – the weight of an ion. Certainly, the double charged ions (which usually make up to 10 % of a flows) can increase F_t. But we suppose that this increase is compensated by the part of ions which born in the acceleration zone, and their final velocity is less than V_U. The real measured jet pulse of the thruster F is determined as follows

$$F = GV_R \qquad (10)$$

As the jet pulse F and the flow rate G are measured directly in experiment, the velocity V_R is easily calculated. In modern thrusters we usually have $V_R \sim 0.8V_U$, i.e F is 20 % less than F_t. The only two basic reasons of the reduction of the real velocity of ions V_R in comparison with theoretical V_U are possible: - 1) the presence of the divergence of the ion jet from its axis, - 2) the part of ions is lost on the channel walls. It is rather simple to take into account the divergence of the ions in the jet, as the distribution of ions flow by angle is known from the measurements of the ion current J on a probe (see, for example, [3])

$$J = eS_{zond} < nV > \qquad (11)$$

From results of measurements it is possible to accept with sufficient accuracy, that the ion density in the jet has the exponential angle distribution (except the region of very small angles)

$$< nV >= I(\gamma) = I_0 \exp(-k\gamma) \qquad (12)$$

Where (k^{-1}) - characteristic angular distance (in radians), on which the value of the ion flow decreases in «e» times (e = 2,71...). As the distribution (12) is measured on the rather large distance from the accelerator in comparison with its size, it is possible to consider, that the velocities of ions are directed along radius. Integrating on a hemisphere, which area let's assume to equal unit, we receive the complete flow of ions I_t

$$I_t = \int_0^{\pi/2} I_0 \exp(-k\gamma)\sin\gamma d\gamma \qquad (13)$$

Only the axial velocity of ions V gives the contribution in the real jet pulse, therefore we need also the integral I_{tx}

$$I_{tx} = \int_0^{\pi/2} I_0 \exp(-k\gamma)\cos\gamma\sin\gamma d\gamma \qquad (14)$$

For integration of (13) and (14) we shall use the following formula

$$\int e^{ax}\sin bx = \frac{a\sin bx - b\cos bx}{a^2+b^2}e^{ax} \qquad (15)$$

Then we receive

$$I_t = I_0\frac{1-ke^{\frac{-\pi k}{2}}}{k^2+1}; \quad I_{tx} = I_0\frac{1+e^{\frac{-\pi k}{2}}}{k^2+4}; \qquad (16)$$

From [3] the characteristic value for k is equal ~ 5, that is for the increase of the angle in 10°-12° the density of ions flow decreases in «e» times. Hence we have

$$\frac{I_{tx}}{I_t} \cong \frac{k^2+1}{k^2+4} = (26/29) \cong 0,9 \qquad (17)$$

The ratio (17) means that about 10 % from the complete (theoretically achievable) pulse F_t of the plasma flow is lost because of the angle divergence of the ions velocities. Hence the other 10 % from 20% difference between F and F_t are lost because of the ions flow in the channel walls.

As a result of above estimations, we have received that the total ions flow in the channel walls for modern thrusters does not exceed 10 % from the total flow of ions.

The analysis of empirical dependences of wear

In one of the first works on the erosion of isolators in Hall thrusters [4] the following empirical dependence for the value of wear "y" from the operating time "t" of the thruster was used

$$y = Ct^n \qquad (18)$$

Where C, n – some experimentally determined constants, which depend on the mode of operations and the material of channel walls.

In the works [5], [2] on the basis of the analysis of the ion dispersion processes the following analytical dependences for the value of the walls wear are offered

$$y = A[1 - \exp(-\omega \cdot t)] \qquad (19)$$

$$y = A[1 - \frac{1}{1+\omega \cdot t}] \qquad (20)$$

$$y = A\ln(1+\omega \cdot t) \qquad (21)$$

Where A and ω - two factors, which are determined empirically. For clearing physical sense of these dependences we use expression (7), namely that fact, that derivative dy/dt is proportional to the flow of ions on a wall <nV>. Then for (19) we receive that this formula corresponds to the linear law dependence <nV> from y, that is, <nV> ~ dy/dt = Aω(1-y/A). Accordingly, for (20) is received the square-law dependence of the flow from y, $dy/dt = A\omega(1-y/A)^2$. For (21) we have exponential dependence dy/dt = Aω·exp(-y/A), and for (18) - hyperbolic dependence $dy/dt = Cn\,(C/y)^{(1-n)/n}$.

The last (hyperbolic) dependence has obvious lack - at any choice of constants C and n (at n < 1) it has infinite initial velocity of wear. To get rid of this lack, it is possible as the initial moment of time to take non-zero value of time t_0, but, obviously, it means the introduction of the additional third empirical factor, besides A and ω.

The statistical analysis of the approximation accuracy of the experimental points by the formulas (19), (20), (21) has shown, that the best accuracy of approximation can be achieved at use of logarithmic dependence (21). It should not surprise, as in (21) is realized the exponential law of change the ion flow from cross coordinate y, namely such dependence <nV> which is closest to the real one. In favor of this the following points testify: first, the character of the angular distribution of a flow of ions in the jet (12), and, secondly, the law of reduction of the ions density from the center to the walls inside the channel (26).

The scale of ions density change in the cross direction

The flow of ions <nV> on the wall changes during the wear of the wall. For a prediction of the dynamics of this wear in time it is important to know the law of the changing <nV> in cross to the flow axis direction, i.e. along "y" axis. It is obvious, that the absolute value of average velocity of ions "v" poorly varies across a flow, because all ions pass practically an identical difference of potential, but the density of ions can change strongly. The density distribution n(y) begins to be formed in the ionization zone, and the final view gets in the acceleration zone. For getting a dependency n(y) in first approach it is possible to use the simplified equations of ionization and motion for ions. As we are interested by changes of the density only from cross coordinate "y", we can use the coordinate system that driven together with ions along the axis "x", in this system v_x disappears. Then the equation of ionization can be written as

$$d(nv)/dy = nn_a\beta \qquad (22)$$

Here β - the rate of ionization, n_a – the density of atoms in plasma, v – the "y" component of ions velocity.

In the assumption that the lines of the magnetic field are perpendicular to an axis "x", the basic force acting on ions along "y", will be the gradient of electronic pressure, as the gradient of the ion pressure can be neglected because of ions temperature is essentially smaller in comparison with electronic one. Certainly the electron pressure acts directly on the electrons only. But as a result the electrons have time to be displaced with respect to ions on very small distances (the value of Debay electron radius in plasma ~ 0.1 mm). So the induced electrical fields occur in plasma, which compensate the gradients of the electronic pressure. And this fields already acts on ions. Thereby the equation of movement for ions can be written as

$$Mnv\frac{dv}{dy} = -T\frac{dn}{dy} \qquad (23)$$

The system of equations (22), (23) in solved with respect to derivatives view may be rewritten as

$$\begin{cases} v' = n_a\beta \cdot v_0^2/(v_0^2 - v^2) \\ n' = nn_a\beta \cdot v/(v^2 - v_0^2) \end{cases}$$

where the designation $v_0^2 = T/M$ is entered. The equation for v does not depend from density n and may be integrated easily. As a result we receive

$$v(1 - v^2/3v_0^2) = \beta \cdot n_a y$$

(24)

The constant of integration is determined from the condition of symmetry of the flow, then at the center of the channel we have v (0) = 0. For regions which are not so far from the center, it is possible to put $v_0^2 >> v^2$. Then we receive that v(y) grows under the linear law $v(y) = \beta \cdot n_a y$, in view of it the second equation of system is integrated also

$$n(y) = n(0)\exp[-(y/L)^2] \qquad (25)$$

Here the designation $L = \sqrt{2}v_0^2/n_a\beta$ is entered. It is obvious that L is the characteristic value, at y = L the density of ions decrease in «e» of time. This value depends on the density of atoms n and the electron temperature T. It is rather simply to estimate the density of atoms if we know the flow rate, the cross section of the channel etc. For example, for the thruster T-100 in the beginning of the ionization zone it can be accepted equal $n_a = 2{\cdot}10^{14}$ cm^{-3}, and in its end and in the layer of acceleration $n_a = 10^{13}$ cm^{-3} (that means 95 % degree of ionization of the flow rate). The electron temperature T in the acceleration zone changes not strongly (T ~ ε_1) and makes usually of several tens eV, depending on a material of walls. The diagram of changing of the characteristic length L from the electron temperature T for $n_a = 10^{13}$ cm^{-3} is given in the fig. 2

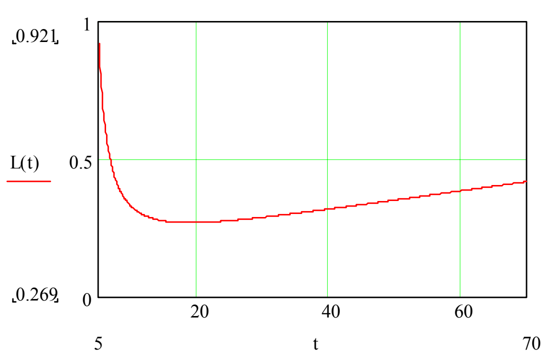

Fig. 2

From the diagram we can see, that the value L varies not so strongly from the temperature. It allows to make a conclusion that the value L, as a rule, will be in a range of 3÷4 mm.

In the conclusion it is necessary to note, that the real dependence n(y) can differ from (25). That's happened mainly because of the curvature of the magnetic field lines, which is especially appreciable near the channel walls. Because of the focusing action of B field, which slows the ions movement on walls, the change of n(y) from "y" in reality is smoother, than it follows from the formula (25). This circumstance can be taken into account, if instead of (25) to take advantage of the following dependence n from "y"

$$n(y) = n(0) \cdot \exp(-y/L) \qquad (26)$$

If we take into account also, that the absolute value of the ions velocity V poorly varies across the channel, we obtain that the change of the flow <nV> from "y" is proportional to the change of density n(y). Thus the advantage, marked in the previous section, of the logarithmic dependence (21) above the other types of the dependences is not casual. This fact is a consequence of that (21) reflects the physics of the process of plasma flow in the channel better. Let's take into account that in the right part of (7) the density of ions "n" is most appreciable from coordinate "y" varies. Then the substitution (26) in (7) results in the following expression

$$\frac{dy}{dt} = \left.\frac{dy}{dt}\right|_{t=0} \exp(-y/L) = C \cdot \exp(-y/L) \qquad (27)$$

Where through C the initial velocity of the wall wear is designated. Integrating (27), we receive

$$y(t) = L \cdot \ln(1 + \frac{C}{L} t), \qquad (21')$$

That is formula (21), only in other designations (A = L, ω = C/L).

The initial velocity of wear

For an estimation of initial velocity of the channel wall wear we use the same base formula (7). It is obvious, that it is enough to us to estimate the ions flow near the wall <nV> and the angle γ of its inclination to the jet axis, as the other values in the right part (7) it is possible to believe known. Let's begin from the angle of an inclination. They usually aspire by the selection of the magnetic field configuration to direct the ions flow along the thruster axis. The basic factor that prevents the focusing the flow is the presence of the cross gradient of the electron pressure (see formula (23)), as already was marked earlier. During the movement in the acceleration zone under the action of force "eEn" in a longitudinal direction the ions will collect energy "neU". And for the same time in a cross direction under the action of force "T(dn/dy)" the ions will collect energy "nT". Thus the attitude of cross and longitudinal ions velocities will be $V_y/V_x = (T/eU)^{1/2}$, and the sine of the inclination angle will be equal

$$\sin\gamma \approx tg\gamma = (T/eU)^{1/2} \qquad (28)$$

The value of the ions flow at the wall can be connected with the mass flow rate of the working body as follows. The average flow through the channel section in the assumption of complete ionization is equal

$$< nV >= G/(MS_c) \quad (29)$$

Where S_c – the area of the cross section of the acceleration channel in its exit. In the assumption of the exponential reduction of the density across an axis (26), the average density through the channel section <n> will be

$$<n>=\frac{2}{b}\int_0^{b/2} n_m \cdot \exp(-y/L)\cdot dy = n_m \frac{2L}{b}(1-\exp(-\frac{b}{2L})) \quad , \quad (30)$$

where b/2 - half-width of the channel. And the density near the wall n will be, accordingly,

$$n = n_m \exp(-b/2L) \quad (31)$$

From (30) and (31) the expression for n through <n> follows

$$n =< n > \frac{b}{2L}\frac{1}{\exp(b/2L)-1} \quad (32)$$

As a result the following expression for an estimation of initial velocity of wear C is received

$$C \equiv \left.\frac{dy}{dt}\right|_{t=0} = \left[\frac{M_w}{\rho} S_w\right]\frac{G}{MS_c}\frac{b}{L}\frac{1}{\exp(b/2L)-1}(T/eU)^{1/2} \quad (33)$$

For characteristic working parameters of the thruster of a type T-100 this formula gives the following value for the initial velocity of the wear: 1) for L = 4 mm is received C≈14 mm / (thousand hours); 2) for L = 3 mm, accordingly, C≈9 (mm / thousand hours). The measurements of the real wear give the initial velocity about ~ 10 (mm / thousand hours), that rather well corresponds to the estimation received by us.

Conclusion

So the dependences (21) and (21') can be recommended for practical use. And here it is expedient to add the following consideration of the most general character. At reception of the dependence of the erosion value "y" from time "t", i.e. finding the function y = f (t), a natural step is the transition to dimensionless parameters. Then the role of factors in the formula (21) becomes clear: C (the dimension of length) is a scale for value of erosion "y", ω (the dimension of return time) - gives dimensionless time. Hence for generalization of experimental data on erosion it is expedient to use two parameters (no more and not less). Just for these parameters the dependences determining them are received.

The formulas, received in the present work, allow to estimate and to predict the values of the wear of the acceleration channel for the Hall type plasma thrusters. And, as the initial parameters for estimations such values are used only which are known already at a stage of development and designing of the new thruster, namely: the geometrical values of the acceleration channel, the properties of a material of its walls, the properties of the working body, the flow rate, discharge voltage. Till now, not having the similar formulas, the estimations of a lifetime for Hall thrusters can be made after measurements of the wear during several hundreds hours of functioning of the thruster on the test vacuum stand. Now we have an opportunity to predict the lifetime of new models of Hall thrusters already at a stage of designing with good accuracy.

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