Analysis of Energy Balance in the Discharge of SPT Using Results of Its Integral Parameters and Plume Characteristics Measurements

IEPC-2009-097

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Abstract: Results of the power flows analysis in the stationary plasma thruster (SPT) discharge are represented in the paper. Such analysis is interesting for experts dealing with researches of the SPT physics. Particularly it is interesting to understand peculiarities of the power flows change with change of thruster operation mode. It is difficult to realize direct measurement of power flows in the discharge chamber. Therefore the indirect methods of their estimation are subject of author's interest. And some possible approaches to solve this task are presented in the paper. They are based on the complex analysis of the integral thruster parameters, local plasma parameters in the thruster accelerating channel and plume characteristics determination results as well as of results of the erosion tests.

I. Introduction

ANALYSIS of the power flows in the discharge is interesting for researchers dealing with the SPT physics. Particularly in Ref. 1 it was shown that with increase of discharge voltage under comparable discharge power the more fast increase of the power flows delivered by the accelerated ions to the discharge chamber walls is observed in comparison with the discharge voltage increase rate and that such increase causes increase of thermal loads on walls and their erosion rate. Unfortunately, it is difficult to organize direct measurements of the power flows in the discharge chamber and in Ref. 1 an attempt was made to estimate power flows to walls with usage of the local plasma parameter measurements by near wall probes as well as to check results of the mentioned estimation by analysis of the wall temperature variation during thruster on/off switchings. But accuracy of these methods are not high. So, it is reasonable to improve possible approaches to solve this task and one of the possible ways of such improvement is considered in the given paper. It is based on the complex analysis of thruster integral parameter measurements, measurements of the local plasma parameter in the accelerating channel by near wall probes, results of the plume characteristics measurements and of thruster erosion tests.

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II.   Some previous estimations of the power flows to the discharge chamber walls

As was mentioned above in Ref. 1 an estimation of the power flows to the discharge chamber walls was made with usage of the plasma parameter measurement results by near wall probes and it was shown that power delivered by the accelerated ions to walls is increased with increase of discharge voltage faster in comparison with the discharge voltage increase rate and that these estimation results are in satisfactory agreement with the power flow estimation on base of analysis of the discharge chamber wall temperature variation during thruster on/off switchings. In Ref. 2 with usage of the same approach an estimation of the power flows to discharge chamber walls of two methodical SPT models was made. One of these models was the well known SPT-100 thruster laboratory model. Particularly the distributions of plasma potential, probe floating potential and ion current density along the external discharge chamber wall were determined by the near wall probes (Fig. 1-2).
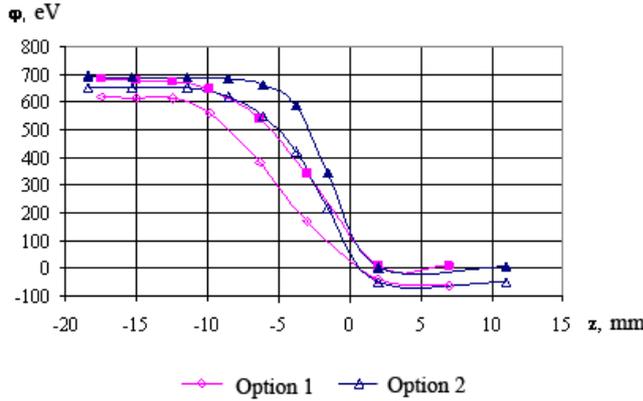

Figure 1. Distributions of the plasma potential φ_{pl} and probe floating potential φ_0 along the discharge chamber external walls of the SPT-100 laboratory model (option 1) and of the methodical model with modified magnetic field (option 2) under discharge voltage 700 V and mass flow rate 2,5 mg/s.
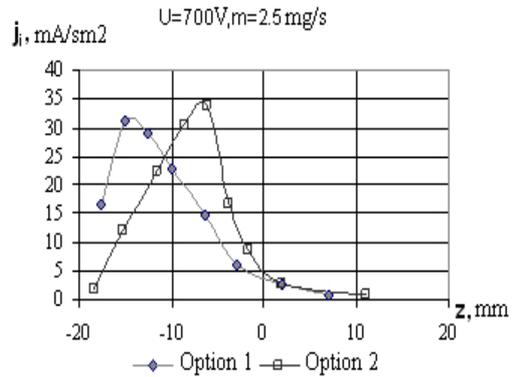
Figure 2. Distributions of the ion current to probe along external discharge chamber wall.

Measurements were made for operation modes with discharge voltages (300-900) V and mass flow rates through the accelerating channel (2-3,5) mg/s. An estimation of the density $q_i(z)$ of power flow delivered by the accelerated ions to the discharge chamber wall was made with usage of obtained results and of the following expression:

$$q_i(z) = j_i(z) \cdot \left[\varphi_{pl} - \varphi_0(z) \right], \tag{1}$$

where as φ_{pl} the values of plasma potential in the near anode zone were chosen for all points taking into account small variation of this potential in the ionization zone (corresponding to the region with maximum ion current to wall) and as a wall potential and ion current density to wall the local values of probe floating potential and ion current to probe were used.

Then, the local values of power delivered by ions to wall were calculated. Integrating distributions of this power density it was possible to estimate the total power N_i' transferred by ions to wall taking into account the ion energy accommodation factor dependence on ion energy as it was determined in Ref. 3. The mean values of this factor was ~(0.6-0.65) that is it was varied within the narrow range. As result the relative values of power $k_n = Q_1''/N_d$ transferred by ions to wall were determined, where $N_d = U_d I_d$ is the discharge power of thruster operating with the discharge voltage U_d and discharge current I_d. Obtained results (Fig. 3) as well as the earlier data [1], show that with increase of discharge voltage the fraction of power transferred by ions to wall is increased.
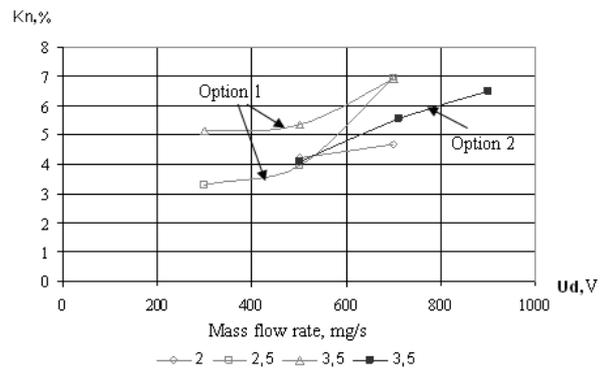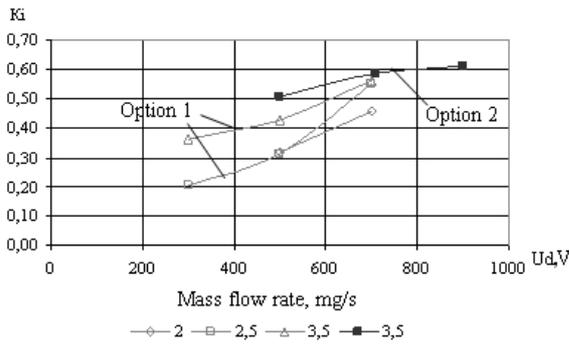
Figure 3. Dependence of the ion current to the SPT-100 laboratory model wall (option 1) on operation mode.

Figure 4. Relative values of power transferred to the external wall under different operation modes.

One can see also that the mentioned fraction is increased with increase of the mass flow rate. One can add that the total ion current I'_{iW} to external wall and its fraction $k_i = I'_{iW}/I_m$, were calculated in Ref. 2, where $I_m = \dfrac{\dot{m}}{M}e$ is the current equivalent to the mass flow rate through the accelerating channel. This fraction is also increased with increase of the discharge voltage (Fig. 4) and this is one of the main reasons for the considered power release increase.

Accuracy of these estimations is not high. Therefore it is interesting to develop some other approaches to analyze power flows in the discharge. One of such possibilities is to restore the ion flow parameters using results of the erosion tests made for the laboratory model of the SPT-100 under operation mode with increased till 700 V discharge voltage [4] and results of the life time test of this thruster [5].

Results of erosion tests allow estimation of power in the ion flow getting wall. Indeed, the local erosion rate of wall due to its sputtering by the ion bombardment $\dot{\xi} = j_i S(\alpha, \varepsilon_i)$, where $j_i, S(\alpha, \varepsilon_i)$ are the ion current density and the sputtering factor under impingement angle at surface α and energy of ions ε_i, respectively. It could be represented [6] as

$$\dot{\xi} = j_i S(\alpha, \varepsilon_i) \approx k_\xi j_i \varepsilon_i \approx k'_\xi q_{iW} , \qquad (2)$$
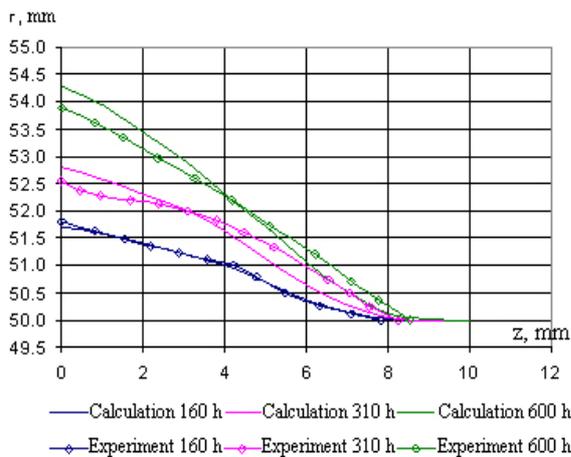

Figure 5. The profiles of the SPT-100 external discharge chamber wall after different duration of its operation [4] (sputtering ability was optimized using profile obtained after 160 hours of thruster operation).
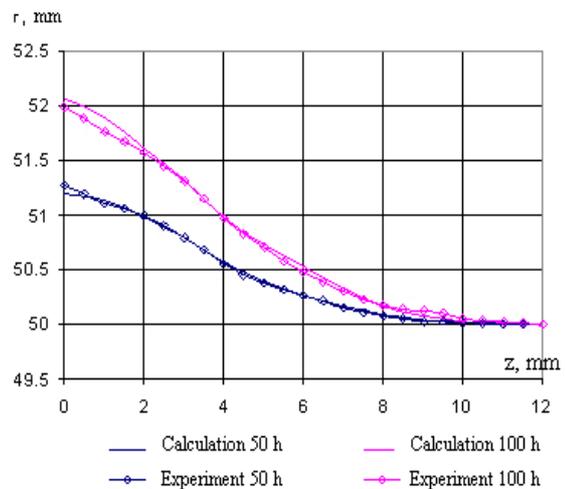

Figure 6. Wall profiles of the SPT-100 laboratory model after different duration of its operation with discharge voltage 700 V and discharge power 1500 W (sputtering ability was optimized using the wall profile obtained after 50 hours of operation).

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where $q_{iW} = j_i \varepsilon_i / e$ is the local sputtering ability of the ion flow really representing its kinetic power density.

And, if the erosion model gives good enough simulation of the erosion process, then one can consider that used in the model sputtering ability is close to real one. Earlier it was shown that model published in Ref. 7 with optimized during simulation sputtering ability distribution gives good enough correspondence with results of tests. Therefore this model was used to restore the ion flow sputtering ability along the external discharge chamber wall and to estimate power Q_2' in the ion flow getting the mentioned wall of the SPT-100 thruster under nominal operation mode with the discharge voltage 300 V [5] and wall of this thruster laboratory model operating with the discharge voltage 700 V and discharge power 1500 W [4].

The corresponding wall profiles under comparable scales of erosion are represented in Fig. 5 and Fig. 6 and results of the sputtering ability restoration – in Fig. 7 and Fig. 8.
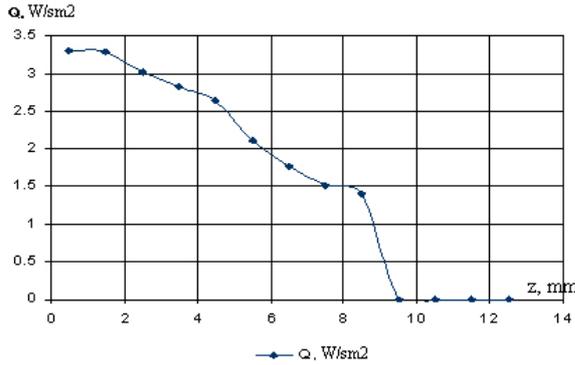

Figure 7. The sputtering ability of the accelerated ions flow getting an external SPT-100 discharge chamber wall under nominal operation mode of thruster with discharge voltage 300 V.
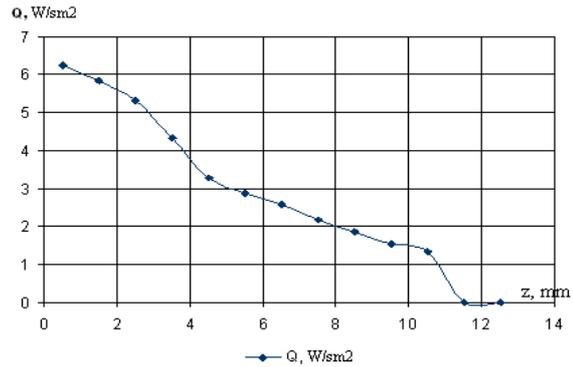
Figure 8. The sputtering ability of the ion flow getting an external wall of the SPT-100 laboratory model operating with discharge voltage 700 V.

Obtained results are represented in the table 1. It's necessary to note that to compare results of the erosion tests Q_2' / N_d and results obtained with the near wall probes one has to take into account that the last ones were calculated with usage of the energy accommodation factor. At the same time results of the erosion tests give an estimation of the kinetic power of the ion flow going to wall. So, it is necessary to use for comparison not the power Q_1'' but power Q_i' in the ion flow calculated according to expression (1). These data are also represented in the table 1. As one can see the difference in data obtained by different methods is great enough but qualitative behavior is similar, namely: with increase of the discharge voltage the fraction of discharge power in the ion flow going to wall is increased. The reasons of the quantitative differences could be an increased relative to real ones plasma potential values during calculation of the ion energy with help of expression (1) and decreased relative to real one ion energy estimation because the sputtering ability of ion flow is assumed equal to zero for part of channel where energy of ions is below sputtering threshold.

To estimate the total power going with ions to both walls one can assume that the current densities at both walls are equal. Then, taking into account difference of the wall surface diameters one can obtain estimated values of total powers Q_1, Q_2 obtained by different methods (see table 1).

Table 1. Results of estimation of the kinetic power in the ion flow getting walls with usage of the local plasma parameter measurements by the near wall probes and results of the erosion tests.

U_d, V	N_d, W	Q_2', W	Q_2' / N_d	Q_2 / N_d	Q_1' / N_d	Q_1 / N_d
300	1350	~63,6	~0,047	~0,08	0,082 ($\dot{m} = 3,5 \, mg/s$)	~0,14
705	1500	~107,7	~0,072	~0,13	~0,1 ($\dot{m} = 2,5 \, mg/s$)	~0,17

All considered data are related only to one fraction of the discharge power. They indicate the necessity to develop other approaches for estimation of the power flows to walls as well as for analysis of the power flow balance for the whole discharge in SPT. One of the possible approaches to solve this task is represented in the next part of paper.

III. An Another possible approach to analysis of the power flow balance in the SPT discharge

An another approach to the power flow balance in the SPT discharge is based on the following. The kinetic power N_{pl} of the plasma flow exhausting thruster could be represented as follows:

$$N_{pl} \approx N_d - N_{los,ch} - N_c ,\qquad(3)$$

where $N_{los.ch}, N_c$ are the parts of the discharge power spent in the discharge volume and to get electrons from cathode, respectively.

Taking into account that fraction of atoms in the exhausting thruster plasma flow and their energy are small in comparison with ion flow and ion energies and that energy delivered by discharge to electrons in the plume is taken into account in the N_c magnitude one can assume that the kinetic power of the whole plasma flow N_{pl} in the plume obtained in the discharge is approximately equal to the kinetic power of the ion flow exhausting thruster, that is

$$N_{pl} \approx \frac{\dot{m}\langle V^2 \rangle}{2} \approx \frac{\dot{m}_i}{2}\langle V_i^2 \rangle ,\qquad(4)$$

where $\dot{m}, \dot{m}_i, \langle V^2 \rangle, \langle V_i^2 \rangle$ are the mass flow rate of propellant through the accelerating channel and mass flow rate of the ion flow, mean value of the ions and atoms velocity squared and ions mean velocity square, respectively.

In turn

$$\frac{\dot{m}_i \langle V_i^2 \rangle}{2N_d} \approx \frac{\dot{m}_i}{2N_d}\langle V_i^2 \rangle \frac{\langle V_i \rangle^2}{\langle V_i \rangle^2}\frac{\langle V_{iz} \rangle^2}{\langle V_{iz} \rangle^2} = \frac{\dot{m}_i}{2N_d}\frac{\langle V_{iz}^2 \rangle}{\eta_v \eta_\beta} = \frac{\dot{m}}{\dot{m}_i}\frac{(\dot{m}_i \langle V_{iz} \rangle)^2}{2\dot{m}N_d \eta_\beta \eta_V} = \frac{(F)^2}{2\dot{m}N_d \eta_m \eta_\beta \eta_V} = \frac{\eta_T}{\eta_m \eta_\beta \eta_V} ,\qquad(5)$$

where $F, N_d = U_d I_d, \langle V_i \rangle, \langle V_{iz} \rangle$ are thrust, discharge power under discharge voltage U_d и and discharge current I_d, mean value of the ions velocity and mean value of the longitudinal ions velocity component, $\eta_m = \frac{\dot{m}_i}{\dot{m}}, \eta_V = \frac{\langle V_i \rangle^2}{\langle V_i^2 \rangle}, \eta_\beta = \frac{\langle V_{iz} \rangle^2}{\langle V_i \rangle^2}, \eta_T = \frac{F^2}{2\dot{m}N_d}$ mass utilization efficiency in the discharge volume (accelerating channel), factors reflecting power losses due to spread of ions in velocities and due to plume divergence, thrust efficiency, respectively.

Taking into account (3) and (5) one can write that

$$N_{los,ch} \approx \left(1 - \frac{\eta_T}{\eta_m \eta_v \eta_\beta}\right)N_d - N_c \qquad(6)$$

Power spent to get electrons from cathode could be determined, if plasma potential $\varphi_{pl.e}$ in the plume is measured

$$N_c = I_d \varphi_{pl.e} \qquad(7)$$

According to the measurements in the SPT plumes with cathodes made of LaB_6 and operating in the so-called automode (without steady state heating) the magnitude of $\varphi_{ple} \approx (20\text{-}30)$ V (see, for example, Ref. 8). Taking this

into account and having results of the thrust efficiency and plume characteristics measurements allowing estimation of the $\eta_m, \eta_V, \eta_\beta$ one can calculate $N_{los,ch}$ value with help of expression (6).

For the fast plume characterization it is convenient to use electrostatic energy analyzer (RPA), positioned at or moving along spherical control surface with great enough radius R and center positioned at the cross-point of the thruster axis and its exit plane. Such system allows determination of the accelerated ions current density $j(R,\beta)$ distribution in off-axis angle β and distribution of ions in energy $f(R,\beta,\varepsilon_i)$ for ions moving along directions with off-axis angle β [8,9]. Having these data and assuming that ion flow has axial symmetry, all ions are moving from the mentioned center of the control surface and that only singly and doubly charged ions are in the plume one can estimate the following magnitudes:

– total ion current in the plume:

$$I_i = 2\pi R^2 \int\limits_0^{\pi/2} j_i(R,\beta)\sin\beta \cdot d\beta, \tag{8}$$

– mass utilization efficiency in the discharge volume (excluding near cathode zone), if one has information on the doubly charged ions in the plume:

$$\eta_m \approx \frac{I_i}{\dot{m}e(1+\mu_2)}M = \frac{2\pi R^2 M}{\dot{m}e(1+\mu_2)}\int\limits_0^{\pi/2} j_i(\beta,R)\sin\beta \cdot d\beta, \tag{9}$$

where $\mu_2 = \dfrac{\dot{m}_{i2}}{\dot{m}_i}, \dot{m}_{i2}, M$ are the fraction of the doubly charged ions, mass flow rate of the doubly charged ions and ion mass, respectively,

– half angle of the accelerated ions flow divergence β_γ for the γ percentage of ions moving within the cone with center positioned at the same center as that one of the control surface:

$$\gamma = \frac{\int\limits_0^{\beta_\gamma} j_i(R,\beta)\sin\beta d\beta}{\int\limits_0^{\pi/2} j_i(R,\beta)\sin\beta d\beta}, \tag{10}$$

Assuming that the distribution functions of the singly and doubly charged ions are the same, one can calculate the following magnitudes:

– mean energy of ions moving along direction with off-axis angle β:

$$\langle \varepsilon_i \rangle(\beta) = \int\limits_0^\infty \varepsilon_i f(R,\beta,\varepsilon_i)d\varepsilon_i, \tag{11}$$

– mean velocity of ions along direction β:

$$\langle V_i \rangle(\beta) = \int\limits_0^\infty \left(\mu_1\sqrt{\frac{2\varepsilon_i}{M}} + \mu_2\sqrt{\frac{4\varepsilon_i}{M}} \right) f(R,\beta,\varepsilon_i)d\varepsilon_i, \tag{12}$$

– mean value of the longitudinal ions velocity component along β:

$$\langle V_{iz}\rangle\langle\beta\rangle = \int_0^\infty \left(\mu_1\sqrt{\frac{2\varepsilon_i}{M}} + \mu_2\sqrt{\frac{4\varepsilon_i}{M}}\right)\cos\beta \cdot f(R,\beta,\varepsilon_i)d\varepsilon_i, \tag{13}$$

– mean value of the ions velocity squared along β :

$$\langle V_i^2\rangle(\beta) = \int_0^\infty \left(\mu_1\frac{2\varepsilon_i}{M} + \mu_2\frac{4\varepsilon_i}{M}\right)f(R,\beta,\varepsilon_i)d\varepsilon_i, \tag{14}$$

– mean ion velocity for the whole plume:

$$\langle V_i\rangle = \frac{2\pi R^2}{I_i}\int_0^\infty \langle V_i\rangle(\beta) j_i(\beta)\sin\beta \cdot d\beta, \tag{15}$$

– mean value of the ion velocity longitudinal component for the whole plume:

$$\langle V_{iz}\rangle = \frac{2\pi R^2}{I_i}\int_0^\infty \langle V_{iz}\rangle(\beta) j_i(\beta)\sin\beta \cdot d\beta, \tag{16}$$

– mean energy of ions in the plume:

$$\langle\varepsilon_i\rangle = \frac{2\pi R^2}{I_i}\int_0^\infty \langle\varepsilon_i\rangle(\beta) j_i(\beta)\sin\beta \cdot d\beta, \tag{17}$$

– mean value of the ions velocity squared

$$\langle V_i^2\rangle = \frac{2\pi R^2}{I_i}\int_0^\infty \langle V_i^2\rangle(\beta) j_i(\beta)\sin\beta \cdot d\beta, \tag{18}$$

– full kinetic power of ions in the plume:

$$W_i = \frac{I_i}{e}\langle\varepsilon_i\rangle, \tag{19}$$

– factor reflecting power losses due to ions flow divergence in the plume:

$$\eta_\beta = \frac{\langle V_{iz}\rangle^2}{\langle V_i\rangle^2}, \tag{20}$$

– factor reflecting power losses due to the spread of ions in velocities:

$$\eta_v = \frac{\langle V_i\rangle^2}{\langle V_i^2\rangle}, \tag{21}$$

– factor reflecting partial use of the applied voltage for the ions acceleration:

$$\eta_\varepsilon = \frac{\langle\varepsilon_i\rangle}{eU_d}, \tag{22}$$

It is necessary to note that measurements of the total ion current in the plume by RPA or electrostatic probes do not give high enough accuracy. So, using these measurements it s difficult to estimate what operation mode gives higher mass utilization efficiency and exact enough value of this factor, particularly due to absence of information on the doubly charged ion fraction. Therefore further analysis is made with two set values of mass utilization efficiency $\tilde{\eta}_m = 0,95$ and $\tilde{\eta}_m = 1,0$. This analysis had shown that under the same distribution of singly and doubly charged ions in energy per single charge the $\eta_\beta, \eta_V, \eta_\varepsilon$ factors are weakly depend on doubly charged ions fraction. Such conclusion is confirmed by estimation of the mentioned factors with usage of the accelerated ions density off-axis distributions and distributions of ions in energy made under different off-axis angles in the plume of the SPT-100 laboratory model [4]. As one can see (table 2), under variation of the doubly charged ions within (0-20)% only factor η_V is changed but not significantly. Other factors are practically are not changed. Therefore for their estimation one can use the ions distributions in energy determined by RPA and not taking into account the doubly charged ions.

Analysis had shown also that under the same mass utilization efficiency and variation of the doubly charged ion fraction in the range of (0-20) % the fraction of power losses within the accelerating channel is changed not more than by 10% (table 2). From the obtained data one can pay attention to significant enough losses due to plume divergence what is understandable taking into account great enough its value. Indeed, for the SPT-100 thruster under nominal operation mode $\beta_{0,95} \approx 45^o$ [9], and laboratory model of this thruster operating with discharge voltage 700 V it is at level 40 degrees [4].

Table 2. Results of the SPT-100 thruster and its laboratory model integral parameter and plume characteristics determination.

$\dot{m}_a$, mg/s	U_d, V	I_d, A	N_d, W	η_t	$\tilde{\eta}_m$	η_V	η_β	η_ε	$N_{los,ch}$, W	$\dfrac{N_{los,ch}}{N_d}$
$\mu_1 = 1,0; \mu_2 = 0$										
4,5	300	4,36	1312	0,52	0,95	0,95	0,82	0,77	280	0,213
4,5	300	4,36	1312	0,52	1,0	0,95	0,82	0,77	328	0,25
2,4	700	2,44	1692	0,52	0,95	0,95	0,85	0,80	483	0,285
2,4	700	2,44	1692	0,52	1,0	0,95	0,85	0,80	541	0,32
$\mu_1 = 0,9; \mu_2 = 0,1$										
4,5	300	4,36	1312	0,52	0,95	0,938	0,82	0,77	271	0,207
2,4	700	2,44	1692	0,52	0,95	0,94	0,85	0,80	471	0,278
$\mu_1 = 0,8; \mu_2 = 0,2$										
4,5	300	4,36	1312	0,52	0,95	0,929	0,82	0,77	260	0,198
2,4	700	2,44	1692	0,52	0,95	0,932	0,85	0,80	496	0,293

It is necessary to note also that η_β factor calculations according to expressions presented above give by ~ 3% larger values than $\langle \cos \beta \rangle^2$ which is used often to estimate influence of the plume divergence on thrust efficiency with usage only ion current density distribution in of-axis angle $j_i(R, \beta)$:

$$\langle \cos \beta \rangle = \frac{\int_0^{\pi/2} \cos \beta \cdot j_i(R, \beta) \sin \beta d\beta}{\int_0^{\pi/2} j_i(R, \beta) \sin \beta d\beta} \qquad (23)$$

Distinguished difference of the η_β and $\langle \cos \beta \rangle^2$ magnitudes determines necessity of measurements of the energy distributions of ions moving along different directions. Such information is useful also for estimation of the plume impact on spacecraft structural elements [9].

Thus, measurements of integral parameters and plume characteristics gives values of $\eta_T, \eta_m, \eta_v, \eta_\beta$ factors and possibility to estimate all parts of discharge power excluding parts of the $N_{los,ch}$. This magnitude could be divided to the following fractions:

$$N_{los,ch} = N_i + N_e , \qquad (24)$$

where N_i, N_e are the powers obtained by ions and electrons, respectively, in the discharge volume excluding that one transferred into kinetic power of ions exhausted into the plume.

During further analysis only power flows in the discharge volume and flows delivered by ions and electrons to this volume boundaries are considered that is the processes on the wall surfaces of the discharge chamber and anode are not considered. Neglecting the thermal conductivity of electron gas the power obtained by electrons in the discharge volume could be presented as follows:

$$N_e \approx N_i'' + (N_{eA} - N_{ec}) + N_{eW} , \qquad (25)$$

where N_i'' s power spent only for ionization and excitation of atoms in the discharge volume, N_{eA} is part of kinetic (thermal) power got by electrons in the discharge and "coming" to anode surface boundary, N_{ec} is thermal power of electrons coming into discharge from cathode and N_{eW} is power got by electrons from discharge and "coming" to the discharge chamber walls.

Estimation of the N_i'' magnitude is complicated task due to difficulty to calculate the radiation losses in the discharge [10]. Therefore one can use an estimation of the ionization cost in the discharge obtained on base of the local plasma parameters in the accelerating channel [11]. According to this estimation the resulting energy cost for ionization is at level of $(3-4)e\varphi_i$ per ion. This cost consists of part of energy spent for the appeared electrons heating. In the given consideration thermal energy in electrons is considered separately. Therefore it is assumed that "pure" energy losses for ionization and excitation of atoms is $\sim 3e\varphi_i$. Taking this into account and determining the total rate of ion production by discharge one can estimate power expenses only for ionization and excitation. According to data presented above (see Fig. 5) in the SPT-100 laboratory model the fraction of ion current I_{iW}' getting external wall under discharge voltage 300 V and mass flow rate 3,5 mg/s is around 35% of current equivalent to the mass flow rate through the accelerating channel (see option 1 in Fig. 5). If one takes into account that for optimized SPT operation modes the current I_i of ions exhausting thruster is close to I_m and that with increase of mass flow rate the fraction of ions getting walls is increased (see Fig.1), then one can estimate this fraction under mass flow rate 4,5 mg/s as $\sim 50\%$. Assuming that ion current densities at external and internal walls are equal and taking into account difference of their diameters one can obtain that total ion current to both walls $I_{iW} \approx 0,8 I_i$.

Similar conclusion could be obtained for operation mode with discharge voltage 700 V and mass flow rate 2,5 mg/s. Indeed, for this operation mode the ion fraction at external wall is $\sim 50\%$ of I_m magnitude. Thus, one can assume that for both operation modes the ion currents going to walls is $I_{iW} \approx 0,8 I_i$. But not all ions are kept by walls. Taking into account that ion energy accommodation factor under ion energies (100-400) eV is $k_2 = (0,6-0,7)$ [3], one can assume that total ion current kept by walls is $k_2 I_{iW}$ and to estimate the total ion production in the discharge as

$$I_{i\Sigma} \approx I_i + k_2 I_{iW} = (1 + 0,8 k_2) I_i \qquad (26)$$

Taking this into account one can estimate the "pure" power expenses for ionization and excitation as

$$N_i'' \approx (1 + 0,8 k_2) I_i \cdot 3\phi_i \qquad (27)$$

Because for the optimized SPT operation modes

$$\frac{I_i}{I_d} \approx 0,8 \approx const \,, \tag{28}$$

an expression (27) with $k_2 \approx 0,6$ could be rewritten as

$$N_i'' \approx 3(1+0,8k_2)I_i\phi_i \approx 3,55I_d\phi_i \tag{29}$$

Power with electrons coming to anode could be represented as

$$N_{eA} = I_{ea}\frac{2kT_{ea}}{e} \,, \tag{30}$$

where I_{ea}, kT_{ea} are electron current and temperature of electros near anode, respectively.

Electron current near anode is practically equal to the discharge current I_d [11].

Concerning the electron temperature in near anode zone it is increased with increase of discharge voltage in the first approximation proportionally to this voltage [1,2], that is:

$$\frac{kT_{ea}}{e} \approx k_1 U_d \,, \tag{31}$$

where $k_1 \approx 0,015$ is numerical factor.

Thus, for N_{eA} calculation one can use the following expression:

$$N_{eA} \approx I_d \cdot 2k_1 U_d \approx 0,03N_d \tag{32}$$

Power coming into discharge with electrons from cathode:

$$N_{ec} \approx I_{ec}\frac{2kT_{ec}}{e} \,, \tag{33}$$

where I_{ec}, kT_{ec} are the electron current coming into discharge and temperature of electrons at cathode side which typical values is (3-5) eV.

For the optimized operation modes:

$$\frac{I_{ec}}{I_d} \approx 0,2 \tag{34}$$

Therefore with $kT_{ec} \approx 5eV$ one can write that

$$N_{ec} \approx I_{ec}\frac{2kT_{ec}}{e} \approx 2I_d \tag{35}$$

Using expressions (24)-(35) one can estimate the power flows "coming" to walls with electrons and accelerated ions as:

$$N_{iW} + N_{eW} \approx N_{los.ch} - N_i'' - (N_{eA} - N_{ec}) \tag{36}$$

Obtained results are represented in the table 3. As one can see here is also definite trend of the "wall" power losses fraction increase with increase of the discharge voltage (see table 3). Considering obtained data one can note

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that power flows to walls under operation mode with discharge voltage 300 V and $\tilde{\eta}_m = 0,95$ are significantly underestimated because estimations of the power flows delivered to walls only by ions with usage of the local plasma parameter measurements and erosion tests give larger their fraction than $\dfrac{N_{iW} + N_{eW}}{N_d}$ obtained by the last method. Therefore for the further estimations the only $\tilde{\eta}_m = 1,0$ is used for this operation mode.

To close an energy balance in discharge one has to estimate power flow N_{eW} coming to walls with electrons. It is natural to consider that electron current is equal to ion current to walls. Then, electrons are moved to wall in the retarding sheath. Therefore one can write that

$$N_{eW} \approx I_{iW}\frac{3kT_e}{2e} \tag{37}$$

Table 3. Results of estimation of power delivered by electrons and accelerated ions to walls.

$\dot{m}_a$, mg/s	U_d, V	I_d, A	N_d, W	$N_{los,ch}$, W	N_{eA}, W	N_{ec}, W	N_i'', W	$N_{iW} + N_{eW}$, W	$\dfrac{N_{iW} + N_{eW}}{N_d}$
4,5	300	4,36	1312	280 ($\tilde{\eta}_m = 0,95$)	39,4	~8,7	~187,3	~62	~0,047
4,5	300	4,36	1312	328 ($\tilde{\eta}_m = 1,0$)	39,4	~8,7	~187,3	~110	~0,084
2,4	700	2,44	1692	483 ($\tilde{\eta}_m = 0,95$)	~50,8	~4,9	~105	~332	~0,196

According to probe measurements an electron temperature near walls is increased with increase of discharge voltage till ~700 V also almost proportionally to discharge voltage [1,2,12], that is

$$\frac{kT_e}{e} \approx k_3 U_d , \tag{38}$$

where according to different sources $k_3 \approx 0,05 - 0,1$.

Taking this into account and assuming $k_3 \approx 0,06$ one can write:

$$N_{eW} \approx I_{iW} \cdot k_2 U_d \approx 0,05 N_d \tag{39}$$

Using this expression one can compare estimations of the total power total power going to walls obtained by different methods (table 4).

Table 4. Comparison of the $N_{iW} + N_{eW}$ estimations by different methods.

$\dot{m}_a$, mg/s	U_d, V	N_d, W	$N_{los,ch}$, W	$N_{iW} + N_{eW}$, W	$\dfrac{N_{iW} + N_{eW}}{N_d}$	$\dfrac{Q_1 + N_{eW}}{N_d}$	$\dfrac{Q_2 + N_{eW}}{N_d}$
4,5	300	1312	328 ($\tilde{\eta}_m = 1,0$)	~110	~0,084	~0,13 ($\dot{m} = 3,5 \ mg/s$)	~0,19
2,4	700	1692	483 ($\tilde{\eta}_m = 0,95$)	~332	~0,196	~0,17 ($\dot{m} = 2,5 \ mg/s$)	~0,22

Obtained data show that results of the power determination by the last method for operation mode with the discharge voltage 300 V are seemed underestimated. The probable reason of this fact is overestimation of the power expenses for ionization and excitation. It seems also that the most close to reality are results of estimations with usage of the erosion test data.

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As a whole an analysis similar to that one which was done allows estimation of the different power flow fractions scales and to distinguish the most uncertain magnitudes in such analysis.

IV. Conclusion

Analysis of the power flow fractions in the SPT discharge was done with usage of different approaches. This analysis shows that it is difficult to close power flows balance due to low accuracy of measurement or estimation of at least several magnitudes such as mass utilization efficiency, energetic cost of the ion production and others. Nevertheless such analysis allows estimation of the different power flow fractions scales in the SPT discharge.

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