

Results of the Plume Characteristics Study for SPT Operation on Different Modes

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Abstract: Nowadays significant enough attention is paid to investigation and development of the stationary plasma thrusters (SPT) with increased specific impulses operating under increased discharge voltages. Some these studies are devoted to the thruster plume characteristics studies. But these studies still not fully enough characterize influence of the operation mode on plume characteristics for thrusters of different scales. Therefore the SPT-100 type and SPT-140 type laboratory model plume characteristics investigation was made to study the trends of their variation with change of thruster operation modes. Particularly the distributions of the accelerated ions in thruster off-axes angles and energy distributions of ions exhausting thruster along different off-axis directions under different operation modes were measured and trends of their variation with change of operation modes are analyzed in the given paper.

The stationary plasma thrusters (SPT) of Morozov's type are successfully used in space technology and scales of their application are extended¹. In this connection the requirements to SPT on thrust, specific impulse and lifetime are strengthened. Particularly nowadays it is interesting to develop SPT with increased specific impulse. Therefore in Russia and other countries the SPT characteristics including their plume characteristics and specifics of their operation under increased discharge voltages ensuring high specific impulses are studied already many years. Nevertheless it is still interesting to investigate general trends of the plume characteristics variation with variation of operation modes of thrusters of different sizes. Therefore the study of the accelerated ion current density distributions in thruster off-axes angles under different operation modes as well as the distributions in energy of ions exhausting thruster in different directions were studied for SPT-100 type and SPT-140 type laboratory models. Obtained results are represented below.

I. Some results of the previous studies and objectives of the given investigation

As it was mentioned above to studies of the SPT plume characteristics were paid already notable attention²⁻⁷. In between already recognized trends of the plume characteristics dependence on operation mode derived from these studies one can note the following ones:

- increase of the discharge voltage at least till (400-500) V and mass flow rate through the accelerating channel the ion current densities in the plume are increased³;
- divergence of the accelerated ion flow is reduced with increase of the discharge voltage till at least (500-700) V and energy of ions in peripheral parts of plume is increased faster than discharge voltage increase⁴;

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– under increase of the mass flow rate through the accelerating channel (for the SPT-140 type thruster) the ion current density in the near axes part of plume is increased faster than in peripheral part of plume⁵;
– with increase of the discharge voltage one can observe increase of the ion current density in the near axes part of plume and reduction of this current density in the peripheral its part what is resulting in reduction of plume divergence⁶.

Connection of the plume characteristics and thrust efficiency was considered in Ref. 7 for the KM-88 type thruster model within the range of discharge voltages (300-1000) V. Unfortunately the raw experimental data obtained with usage of the retarding potential analyzer (RPA) were not published in Ref. 7 but only reduced ones. Particularly, to estimate thrust losses due to spread of ions in energy the following factor was used:

$$\gamma_E = \frac{\int_0^\infty dU \int_0^{\pi/2} d\beta \sin \beta \cos \beta \sqrt{U} \frac{\partial j_i(\beta, U)}{\partial U}}{\sqrt{U_d} \int_0^{\pi/2} d\beta \sin \beta \cos \beta j_i(\beta, 0)}, \quad (1)$$

where U and $j_i(\beta, U)$ are the retarding potential of the RPA and the ion current density to collector under potential U and off-axes direction of measurement β .

For estimation of plume divergence influence the next factor was used:

$$\gamma_\beta = \frac{\int_0^{\pi/2} d\beta \sin \beta \cos \beta j_i(\beta, 0)}{\int_0^{\pi/2} d\beta \sin \beta j_i(\beta, 0)}, \quad (2)$$

representing a mean cosine of the ion movement directions off-axes angle in the plume.

According to data obtained in Ref. 7 the γ_E and γ_β magnitudes were monotonously increased with increase of the discharge voltage. There are were obtained also the mass utilization factor η_m values which could be estimated comparing the measured values of thrust efficiency η_T and factors γ_E , γ_β and $\eta_I = \frac{I_i}{I_d}$, where I_i and I_d are the current of ions leaving thruster and the discharge current, respectively.

It is necessary to note that factors γ_E and γ_β not fully reflect influence of plume divergence and other factors on losses of thrust and thrust efficiency. Indeed, it seems reasonable to use ratio of the longitudinal ion velocities mean value $\langle V_{iz} \rangle$ to mean value of these velocities $\langle V_i \rangle$ for the whole plume to characterize influence of the plume divergence on thrust losses:

$$\eta_{\beta T} = \frac{\langle V_{iz} \rangle}{\langle V_i \rangle}. \quad (3)$$

Because the γ_β factor is calculated not accounting for impact of the ion distribution in velocities the γ_β and $\eta_{\beta T}$ have to have different values in principle.

Concerning the γ_E factor one can see that really there is a magnitude proportional to mean value of the longitudinal ion velocity for the whole plume in the numerator of expression (1), if one neglects an impact of the off-axes ion current distribution. And magnitude proportional to the possible ion velocity $V_i = \sqrt{\frac{2eU_d}{M}}$ is in denominator.

Thus, this factor can give general characteristics of losses but do not allow detailed characterization of losses. Particularly, it does not allow distinguishing of losses due to plume divergence, due to the ions spread in velocities and due to not full usage of applied discharge voltage for ions acceleration due to power losses in discharge.

Some another approaches to characterize connection of plume parameters and thrust efficiency is known also. For example, the following expression for the thrust efficiency was presented in Ref. 8 assuming that only singly charged ions are in the plume:

$$\eta_T = \frac{\dot{m}_a \langle V_z \rangle^2}{2N_d} \approx \frac{I_i}{I_d} \eta_m \eta_\beta \eta_V \eta_\epsilon. \quad (4)$$

The factors in the right part of expression (1.4) $\eta_m = \frac{\dot{m}_i}{\dot{m}_a}$, $\eta_\beta = \frac{\langle V_{iz} \rangle^2}{\langle V_i \rangle^2}$, $\eta_V = \frac{\langle V_i \rangle^2}{\langle V_i^2 \rangle}$ and $\eta_e = \frac{\langle \varepsilon_i \rangle}{eU_d}$ reflect influence of the mass utilization efficiency, plume divergence, spread of ions in velocities and not full usage of applied voltage for the ions acceleration, respectively.

Magnitudes \dot{m}_a , \dot{m}_i , $\langle V_z \rangle$, $\langle V_i^2 \rangle$, N_d , U_d and $\langle \varepsilon_i \rangle$ are the total mass flow rate through the accelerating channel, mass flow rate of ions, mean longitudinal velocity of flow, ion velocity squared mean value, discharge power, discharge voltage and mean energy of ions, respectively.

As was noted an expression (4) was obtained not accounting for the multiply charged ions impact. Measurement of the doubly charged ions in the whole plume is complicated enough. The simplest way to take them into account is to assume that only singly and doubly charged ions are in the plume and that fraction of the doubly charged ions is the same in all parts of plume. Then, assuming that space and energy distributions (per single charge) of ions are identical for singly and doubly charged ions one can add one more multiplier in the right part of the expression (4):

$$\eta_{v\mu} = \frac{\left[1 + (\sqrt{2} - 1)\mu_2\right]^2}{(1 + \mu_2)^2}, \quad (5)$$

where μ_2 is the mass fraction of the doubly charged ions.

So, having results of measurements at least in one point of plume one can estimate impact of the doubly charged ions on thrust efficiency.

Taking into account difficulty of the accurate enough measurements of the multiply charged ions fraction in the whole plume some attempts were made to estimate fraction of the doubly charged ions having integral thruster parameter measurements (see, for example, Ref. 4.9). In the given paper these attempts were continued with usage of the integral thruster parameters determination and plume characteristics measurements, namely: as in some other works with help of the retarding potential analyzer (RPA) there were made measurements of the accelerated ions current density distributions along the spherical control surface with radius R and center in the cross point of thruster axes and its exit plane. As result the accelerated ion current density distribution $j(R, \beta)$ in the off-axes angle β and energy distribution function $f(R, \beta, U_a)$ for ions moving along direction with off-axes angle β were determined, where $U_a = \varepsilon_i / e$ is the potential corresponding to energy ε_i . Then, for each operation mode the thrust efficiency and specific impulse were determined also. Assuming that:

- all ions are started from the mentioned center,
- only singly and doubly charged ions are in the plume,
- fraction μ_2 of the doubly charged ions, their space and energy distributions (per single charge) are the same in the whole plume, one can use the following expression to estimate the plume parameters:
- the total current of the accelerated ions:

$$I_i = \int_0^{\pi/2} 2\pi R^2 j_i(R, \beta) \sin \beta d\beta; \quad (6)$$

a half angle β_γ of cone (with the same center and axes as the mentioned control surface has) through which the fraction γ of the ion current is passed:

$$\gamma = \frac{1}{I_i} \int_0^{\beta_\gamma} 2\pi R^2 j_i(R, \beta) \sin \beta d\beta; \quad (7)$$

- the fractions of singly and doubly charged ions μ_1 and μ_2 :

$$\mu_1 = \frac{\dot{m}_{i1}}{\dot{m}_i}, \quad \mu_2 = \frac{\dot{m}_{i2}}{\dot{m}_i}, \quad \mu_1 + \mu_2 = 1, \quad (8)$$

where \dot{m}_i is the mass flow rate of all ions, \dot{m}_{i1} and \dot{m}_{i2} are the mass flow rates of singly and doubly charged ions, respectively;

- a mass utilization efficiency factor:

$$\eta_m \approx \frac{I_i M}{\dot{m}_a e (1 + \mu_2)}, \quad (9)$$

where M and e are the mass of ions and electric charge, respectively;

– mean energies of singly charged and doubly charged ions $\langle \varepsilon_{i1} \rangle$ и $\langle \varepsilon_{i2} \rangle$ moving along direction with off-axes β :

$$\langle \varepsilon_{i1} \rangle (\beta) = \int_0^{\infty} eU_a f(R, \beta, U_a) dU_a, \quad (10)$$

$$\langle \varepsilon_{i2} \rangle (\beta) = \int_0^{\infty} 2eU_a f(R, \beta, U_a) dU_a = 2 \langle \varepsilon_{i1} \rangle (\beta);$$

– mean velocities $\langle V_{i1} \rangle$ and $\langle V_{i2} \rangle$ of the singly and doubly charged ions along direction β :

$$\langle V_{i1} \rangle (\beta) = \int_0^{\infty} \sqrt{\frac{2eU_a}{M}} f(R, \beta, U_a) dU_a, \quad (11)$$

$$\langle V_{i2} \rangle (\beta) = \int_0^{\infty} \sqrt{\frac{4eU_a}{M}} f(R, \beta, U_a) dU_a;$$

– mean values of the longitudinal ion velocity components $\langle V_{i1} \rangle$ and $\langle V_{i2} \rangle$ along direction β :

$$\langle V_{iz1} \rangle (\beta) = \int_0^{\infty} \sqrt{\frac{2eU_a}{M}} \cos \beta f(R, \beta, U_a) dU_a, \quad (12)$$

$$\langle V_{iz2} \rangle (\beta) = \int_0^{\infty} \sqrt{\frac{4eU_a}{M}} \cos \beta f(R, \beta, U_a) dU_a;$$

– the ions mean square velocities $\langle V_{i1}^2 \rangle$ and $\langle V_{i2}^2 \rangle$ of singly and doubly charged ions along direction β :

$$\langle V_{i1}^2 \rangle (\beta) = \int_0^{\infty} \frac{2eU_a}{M} f(R, \beta, U_a) dU_a, \quad (13)$$

$$\langle V_{i2}^2 \rangle (\beta) = \int_0^{\infty} \frac{4eU_a}{M} f(R, \beta, U_a) dU_a;$$

– mean energy of ions along direction β :

$$\begin{aligned} \langle \varepsilon_i \rangle (\beta) &= \mu_1 \langle \varepsilon_{i1} \rangle (\beta) + \mu_2 2 \langle \varepsilon_{i1} \rangle (\beta) = \\ &= (\mu_1 + 2\mu_2) \langle \varepsilon_{i1} \rangle (\beta) = (1 + \mu_2) \langle \varepsilon_{i1} \rangle (\beta); \end{aligned} \quad (14)$$

– mean velocity of ions along direction β :

$$\begin{aligned} \langle V_i \rangle (\beta) &= \mu_1 \langle V_{i1} \rangle (\beta) + \mu_2 \langle V_{i2} \rangle (\beta) = \\ &= \int_0^{\infty} \left(\mu_1 \sqrt{\frac{2eU_a}{M}} + \mu_2 \sqrt{\frac{4eU_a}{M}} \right) f(R, \beta, U_a) dU_a; \end{aligned} \quad (15)$$

– mean value of the longitudinal ion velocity component along direction β :

$$\begin{aligned} \langle V_{iz} \rangle (\beta) &= \mu_1 \langle V_{iz1} \rangle (\beta) + \mu_2 \langle V_{iz2} \rangle (\beta) = \\ &= \int_0^{\infty} \left(\mu_1 \sqrt{\frac{2eU_a}{M}} + \mu_2 \sqrt{\frac{4eU_a}{M}} \right) \cos \beta f(R, \beta, U_a) dU_a; \end{aligned} \quad (16)$$

– mean square velocity of ions along direction β :

$$\begin{aligned} \langle V_i^2 \rangle (\beta) &= \mu_1 \langle V_{i1}^2 \rangle (\beta) + \mu_2 \langle V_{i2}^2 \rangle (\beta) = \\ &= \int_0^{\infty} \left(\mu_1 \frac{2eU_a}{M} + \mu_2 \frac{4eU_a}{M} \right) f(R, \beta, U_a) dU_a. \end{aligned} \quad (17)$$

– mean value of ions velocity for the whole plume:

$$\langle V_i \rangle = \frac{2\pi R^2}{I_i} \int_0^{\pi/2} \langle V_i \rangle (\beta) j_i(R, \beta) \sin \beta d\beta; \quad (18)$$

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

$$\langle V_{iz} \rangle = \frac{2\pi R^2}{I_i} \int_0^{\pi/2} \langle V_{iz} \rangle (\beta) j_i(R, \beta) \sin \beta d\beta; \quad (19)$$

– mean square velocity of ions for the whole plume:

$$\langle V_i^2 \rangle = \frac{2\pi R^2}{I_i} \int_0^{\pi/2} \langle V_i^2 \rangle (\beta) j_i(R, \beta) \sin \beta d\beta; \quad (20)$$

– full kinetic power of the plume ion flow:

$$W_i = \frac{I_i}{e} \langle \varepsilon_i \rangle; \quad (21)$$

– factor of thrust losses due to plume divergence according to expression (3);

– factors reflecting energy losses due to plume divergence, spread of ions in velocities and not full usage of applied voltage for the ions acceleration:

$$\eta_\beta = \frac{\langle V_{iz} \rangle^2}{\langle V_i \rangle^2}; \quad (22)$$

$$\eta_V = \frac{\langle V_i \rangle^2}{\langle V_i^2 \rangle}; \quad (23)$$

$$\eta_\varepsilon = \frac{\langle \varepsilon_i \rangle}{eU_d}. \quad (24)$$

To estimate fraction of the doubly charged ions and all other represented above parameters one more expression was used, namely:

$$gI_{sp} = \eta_m \langle V_{iz} \rangle, \quad (25)$$

where g and I_{sp} are the free fall acceleration factor and measured specific impulse magnitude.

Varying μ_2 magnitude one can calculate all parameters and to find its value satisfying equation (25). Naturally to obtain acceptable results it is necessary to have high enough accuracy of all measurements what is not so simple. Some results are presented in the next part of paper confirming that the presented approach could be acceptable. If so, one can obtain estimation of all considered parameters and factors.

Thus, the main objectives of work presented in the given paper were as follows:

– to distinguish new and to check the found earlier trends of the plume parameter variation with variation of the operation mode;

– to estimate factors reflecting connection of the plume parameters with SPT thrust efficiency and their variation with variation of the operation mode.

These objectives were achieved by study of the integral and plume characteristics of the SPT-100 type and SPT-140 type laboratory models of different sizes under operation modes with increased discharge voltage.

II. Methodology and main results of investigations

A. Methodology of measurements

The mentioned SPT-100 and SPT-140 laboratory models have the same external accelerating channel diameters (100 mm and 140 mm, respectively) and general design diagrams as the corresponding thrusters developed at Fakel design bureau (FDB). They were tested under operation modes with discharge voltages till 1000 V under thruster operation with optimized magnetization currents and measurements of their integral and plume characteristics at each voltage. As result there were determined the thrust efficiency and specific impulse as well as the ion current distributions $j(R, \beta)$ in thruster off-axes angles and distributions in energy $f(R, \beta, U_a)$ of ions moving along directions with different off-axes angles β . The plume characteristics were measured by the RPA probe which was moved within the plane consisting of thruster axes and along circle with radius $R = 0.7$ m and center in the cross point of thruster axes and of its exit plane (Fig. 1). During measurements of the ion current distributions the retarding potential +50 V was used relative to cathode ensuring shift of the retarding grid around +(20-30) V relative to plasma in order to suppress "plasma ion current" to the RPA collector.

During the energy distribution determination only ion current values to the RPA collector for retarding potentials over +50 V relative to cathode were processed.

B. Main results of measurements

Results of plume measurements show the following:

1. Trend of the ion current variation is reduced to increase of the ion current densities in the most part of plume with increase of the discharge voltage (Fig. 2). Character of changes is more evident, if one considers the relative ion current distributions (Fig. 3) showing evident "narrowing" of plume with increase of the discharge voltage and this trend is general for thrusters of two different sizes (Fig. 4). And as was shown earlier this is causing reduction of the plume divergence angle at least till (500-700) V. Over these values of the discharge voltage it is stabilized or even increased what could be connected with change of thruster operation⁴, probably, due to limited capabilities of at least SPT-100 lab model magnetic systems. Taking into account that analogous trend was found in other studies⁵⁻⁶ one can conclude that it is general one for the SPT.

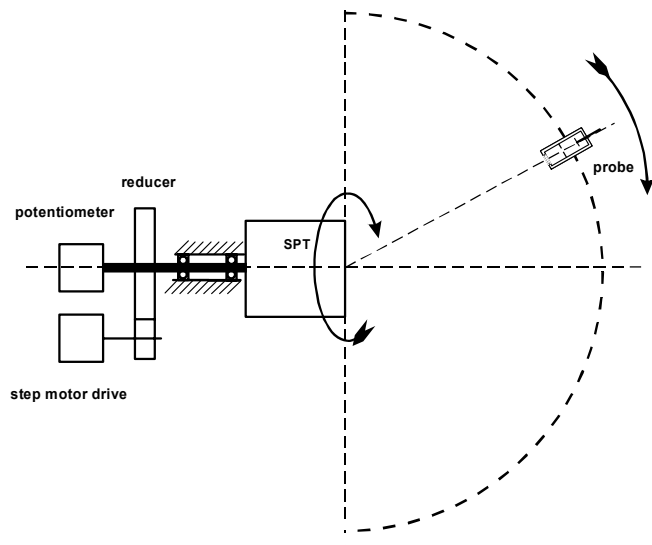


Figure 1. Scheme of the RPA movement.

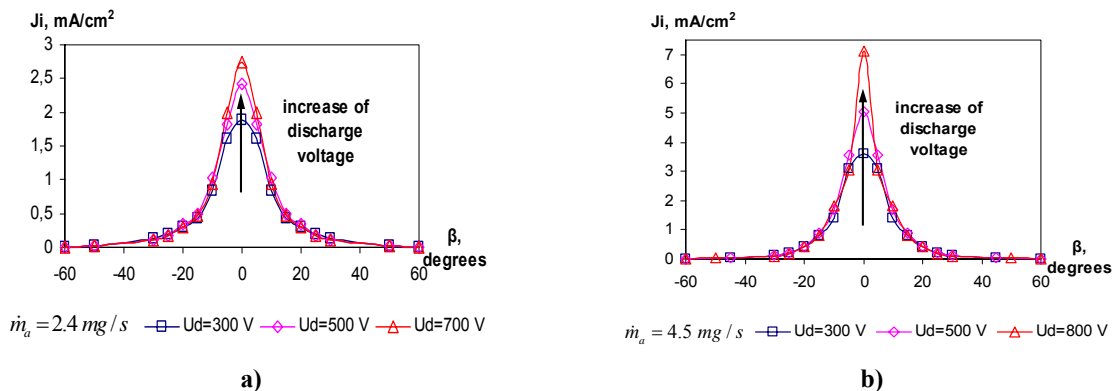


Figure 2. The accelerated ion current density off-axes distributions in the SPT-100 (a) and SPT-140 (b) laboratory model plumes under different discharge voltages.

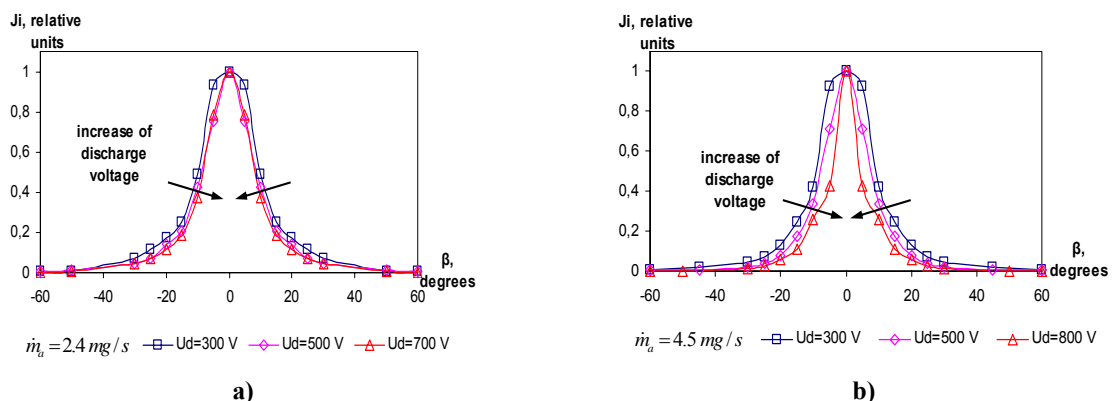


Figure 3. The relative accelerated ion current density distributions in off-axes angles in the SPT-100 (a) and SPT-140 (b) laboratory model plumes under different discharge voltages.

2. Results of the energy distributions determination show that as earlier^{2,6} with increase of the off-axis angle the high energy part of distribution function is reduced. In the near axes part of flow the width of the energy distribution is not much varied with increase of the discharge voltage (Fig. 5,6).

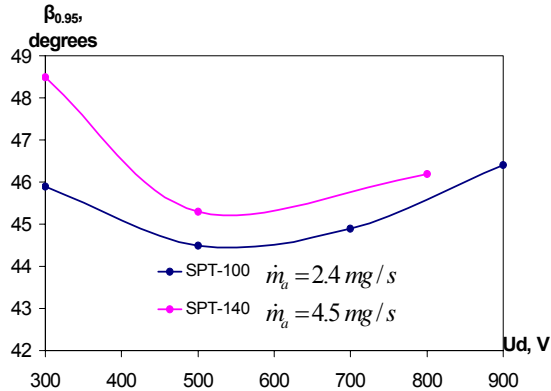


Figure 4. Dependence of the plume divergence angles on the discharge voltage.

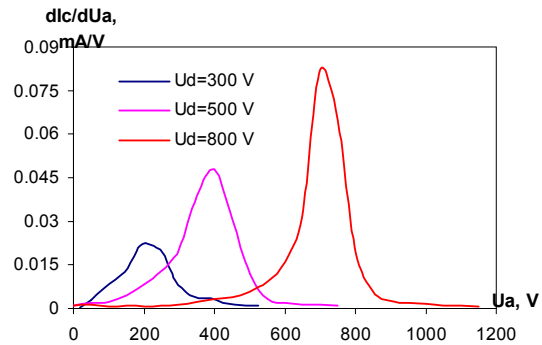


Figure 5. Variation of the ion energy distributions in the near axes part ($\beta = 0$) of the SPT-140 plume with variation of the discharge voltage.

This is an indication of the relatively small changes of the potential drop ΔU within the so-called ionization zone with increase of the discharge voltage (Fig. 6).

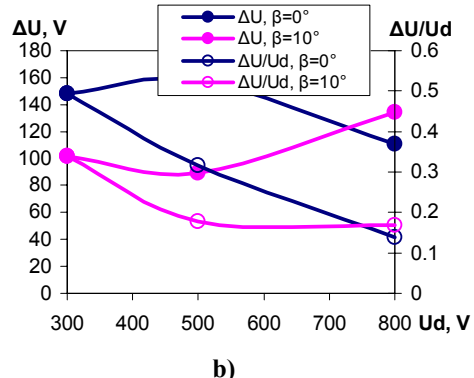
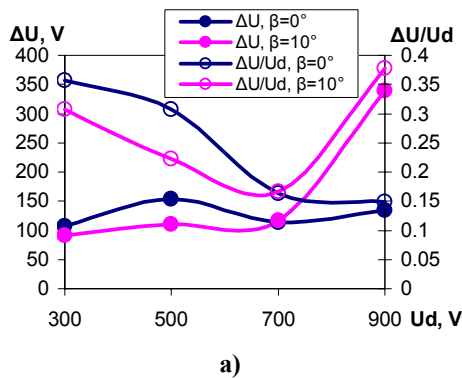


Figure 6. Dependences of the energy distribution half width absolute and relative values on the discharge voltage in the near axes parts of the SPT-100 (a) and SPT-140 (b) type laboratory model plumes.

3. Consideration of the mean ion energy dependence on the discharge voltage shows that besides general increase of its magnitude one can distinguish the higher relative energy of ions in the peripheral parts of plume under lower mass flow rate and low discharge voltages in the SPT-100 laboratory model plume (Fig. 7). This is less evident for the SPT-140 lab model plume (see Fig. 7b) what could be, probably, connected with relatively higher mass flow rate in this case.

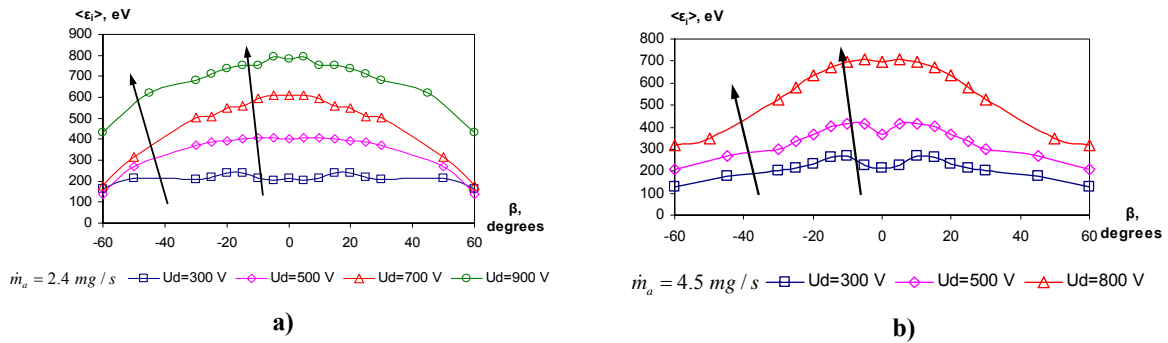


Figure 7. Distributions of the mean ion energy in off-axis angles in the SPT-100 (a) and SPT -140 (b) type laboratory model plumes under different operation modes.

Because the mentioned trends depend on mass flow rate and discharge voltage it is interesting to distinguish influence of the mass flow rate only (Fig. 8).

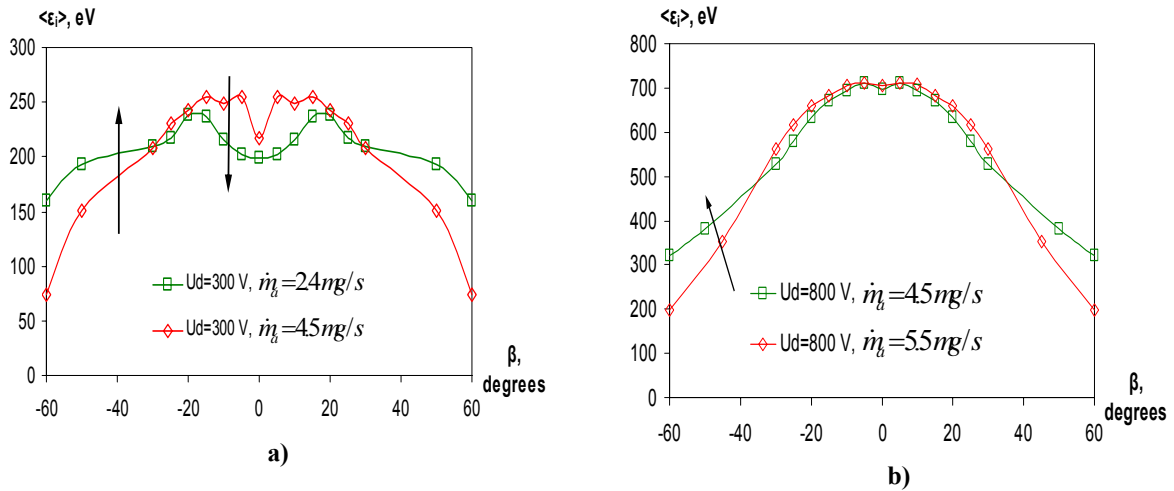


Figure 8. Mean ion energy off-axis distributions in the SPT-100 (a) and SPT-140(b) type laboratory model plumes under different operation modes.

As one can see with reduction of the mass flow rate through the accelerating channel the mean ion energies in the peripheral parts of plume is higher. In combination with the plume divergence increase with reduction of the mass flow rate the mentioned trend could be explained by the worth ion flow focusing with reduction of this mass flow rate.

4. Concerning connection of thrust efficiency and plume parameters one can note the following:

a. The total current I_i of ions exhausting thruster at high discharge voltages is notably higher than current

$I_m = \frac{\dot{m}_a}{M} e$ equivalent to the mass flow rate through the accelerating channel (Fig. 9). This is an indication of the notable multiply charged ion fraction in the plume and, probably, with increase of the secondary electron emission current because in these experiments the suppression of this current was not used.

b. Ratio of the ion current I_i to discharge I_d is approximately equal to 0.8 for the SPT-100 type model and is slowly changed with increase of the discharge voltage. For the SPT-140 model it is higher what is an indication of this model better operation confirmed by higher thrust efficiency of this model.

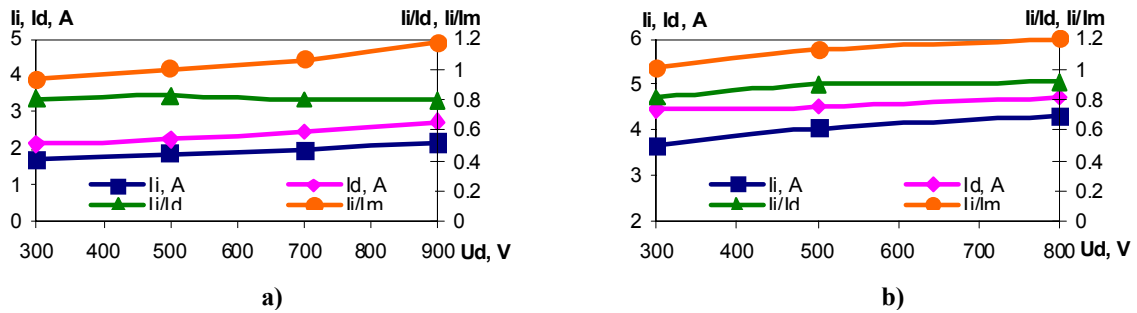


Figure 9. Dependences of the ion current I_i , of the discharge current I_d and of the I_m current on the discharge voltage (a – for the SPT-100 under $\dot{m}_a = 2.4$ mg/s, b – for the SPT-140 under $\dot{m}_a = 4.5$ mg/s).

c. Using obtained plume measurements data and results of the direct thrust measurements the plume parameters and the doubly charged ions fraction was estimated with help of expressions represented in the part 1 of this paper. These estimations had shown (Fig. 10) that the mentioned fraction under increased discharge voltages can reach the level of 20%.

Mean energy of ions is increased with increase of the discharge voltage very similar for SPT-100 and SPT-140 models (Fig. 11). Naturally the mean values of the longitudinal velocity is also increased (Fig. 12).

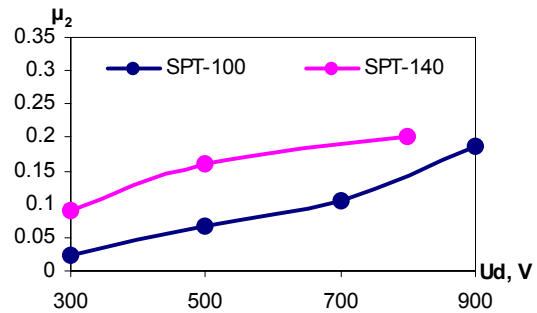


Figure 10. Dependence of the doubly charged ion fraction estimation on the discharge voltage.

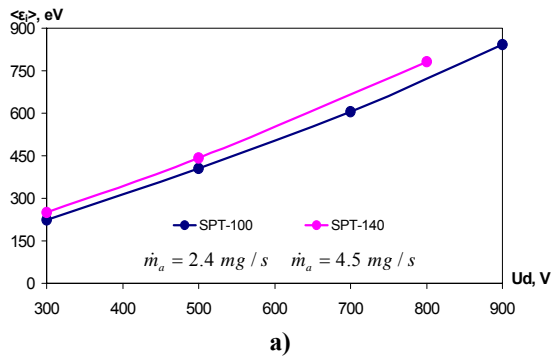


Figure 11. Dependence of the mean ions energy in the plume.

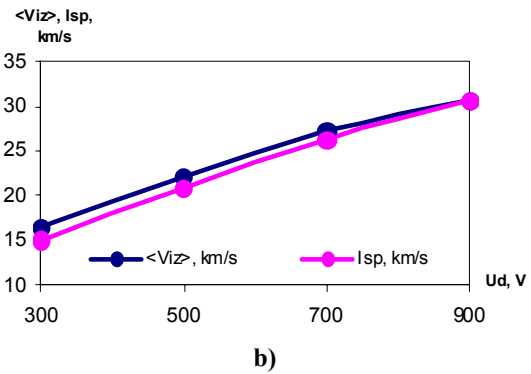


Figure 12. Dependences of the longitudinal ion velocity component mean values calculated with usage of the plume measurements and of the direct measurements of the SPT-140 model specific impulse.

d. Mass utilization efficiency is increased with increase of the discharge voltage till values close to 1 under increased discharge voltages (Fig. 13).

e. The factor η_v is great enough and is slightly reduced with increase of the discharge voltage (see Fig. 13). Thus, spread of ions in velocities has relatively weak impact on thrust efficiency.

f. The most significant influence on thrust efficiency have mass utilization efficiency, especially at low discharge voltages, plume divergence and not full usage of the applied voltage for the ions acceleration (see Fig. 13) characterizing energy losses for the ionization and excitation of the propellant atoms, losses on the walls and partially for the electrons heating, transport them from cathode and discharge volume to anode.

g. Difference of the $\eta_{\beta T}$ and γ_{β} values can reach (1.5-2)%, and difference of the $\eta_{\beta} = \eta_{\beta T}^2$ and $\gamma_{\beta}^2 = \cos^2 \beta >^2$ factors could be (3-4)%. So, this difference is not significant but for the accurate calculations the $\eta_{\beta T}$ and $\eta_{\beta} = \eta_{\beta T}^2$ values are to be used for analyses.

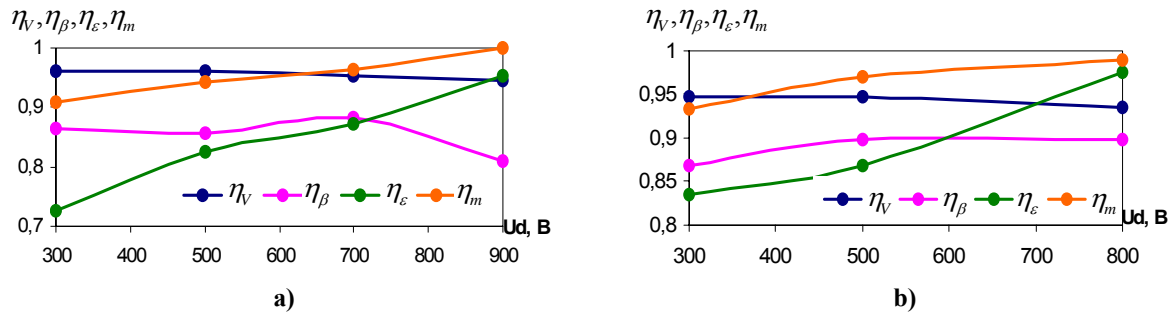


Figure 13. Dependences of the different loss factors on the discharge voltage for the SPT-100 model (a) operating with $\dot{m}_a = 2.4$ mg/s and for the SPT-140 model (b) operating with $\dot{m}_a = 4.5$ mg/s.

Obtained data on factors reflecting connection of the plume parameters with thrust efficiency could be used for calculation thrust efficiency according to expression (1.4) that is using only these factors. Comparing results of this calculation with results of direct thrust efficiency measurements one can estimate the influence of the measurement errors and accepted assumptions on the mentioned factors determination. Such comparison shows that there is (3-5)% difference at low discharge voltages and it is increased till ~10% at high discharge voltages. So, it is necessary to reduce measurement errors as well to improve assumptions. Particularly it should be useful to improve at least the methodology of the accelerated ions current measurements because presented above results were obtained without electron current suppressing at RPA collector. Therefore it seems that this current was overestimated under increased discharge voltages due to increase of the ion energies and secondary electron emission.

As a whole the represented data show that described approach could be used for analysis of factors reducing thrust efficiency.

C. Some additional notes

Concerning physical nature of some obtained trends one can note that small number of studies was made which could be used for analysis of the mentioned nature. In between them one can use results of the local plasma parameter measurements in the accelerating channel by the near wall probes¹⁰. Results of these measurements show that with reduction of the mass flow rate through the accelerating channel the ionization and accelerating layer is extended into anode direction what is confirmed by the corresponding shift of the plasma potential distributions (Fig. 14) and distributions of the ion current densities to the discharge chamber wall (Fig. 15). Such shift has to increase fraction of the ion flow getting walls. These ions are neutralized on wall and then could be ionized and accelerated again. Ions appeared closer to thruster exit have more possibilities to move along directions with larger off-axes angles. Thus, an increase of such ions fraction will cause increase of the plume divergence what is observed in experiments.

One can see also (Fig. 15) that the ion current densities are close to maximum values in the part of channel where potential drop does not exceed (100-150) V and this potential drop is changed not too much with increase of the discharge voltage (see Fig. 14b). This is the reason of the relative stability of the energy distribution half width noted earlier.

Concerning the dependence of the plume divergence on the discharge voltage one can consider the level of the electron temperatures in the zone with ion currents to wall close to their maximum values where longitudinal potential drop is still small (ionization zone) obtained with the same probes (Fig. 16).

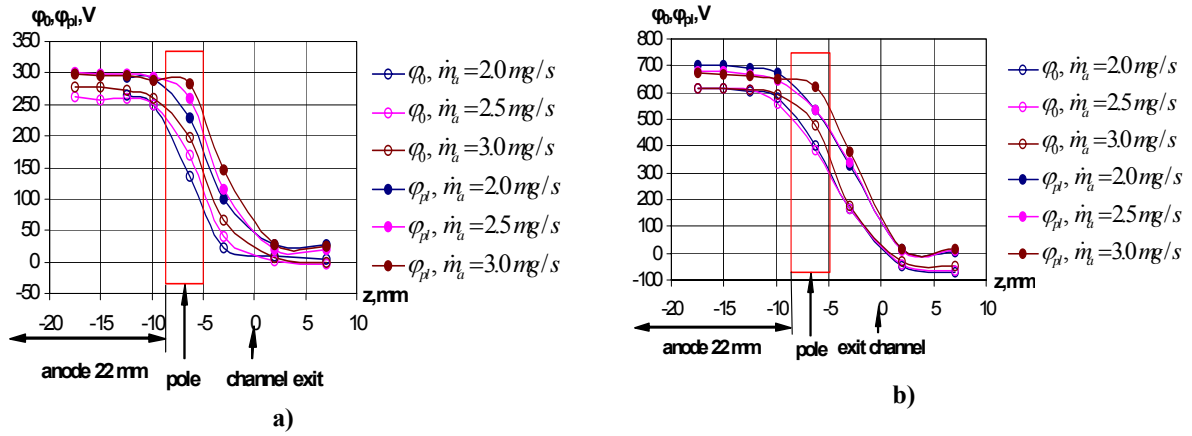


Figure 14. Distributions of the probe floating potential φ_0 , plasma potential φ_{pl} along the SPT-100 model accelerating channel under discharge voltages 300 V (a) and 700 V (b) and different mass flow rates.

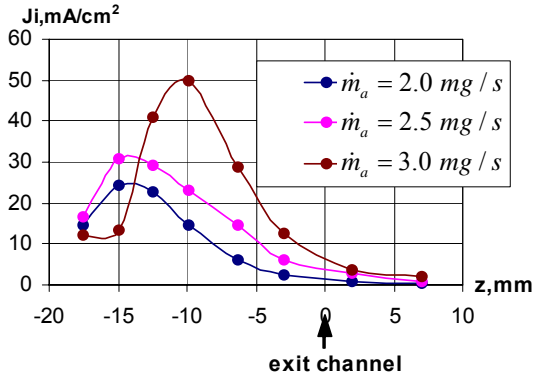


Figure 15. Distributions of the ion current to probe j_i along the SPT-100 model accelerating channel under 700 V discharge voltage and different mass flow rates.

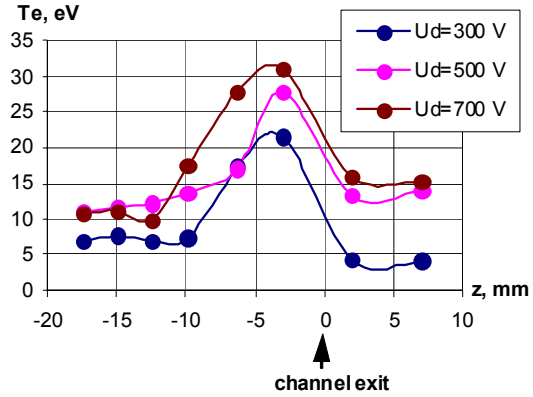


Figure 16. Distributions of the electron temperature T_e along the SPT-100 type lab model accelerating channel under mass flow rate 2.5 mg/s and different discharge voltages.

Taking into account the relatively small potential drop within the ionization zone and high enough temperature of electrons one can imagine that electrons are able to draw ions in radial direction due to their pressure gradient. One can estimate also the corresponding mean radial ion velocities $\langle V_{ir} \rangle$ with usage of obtained electron temperature maximum as

$$\langle V_{ir} \rangle \sim \sqrt{\frac{kT_{e \max}}{e}} \quad (26)$$

as well as to estimate the kind of "mean plume divergence half angle" θ using expression

$$\operatorname{tg} \theta = \frac{V_{ir}}{\langle V_{iz} \rangle} \quad (27)$$

This "mean plume divergence half angle" could be compared with the direction of the "mean" part of ion flow with half angle $\beta_{0.5}$ (Fig. 16). Such, very rough comparison shows that the trends of their variation at least till discharge voltages (500-600) V are similar.

Concerning their behavior for the higher discharge voltages as was noted above operation of the tested model over 700 V is changed significantly. So, this change could be the reason of the corresponding trend change and requires an another approach for explanations.

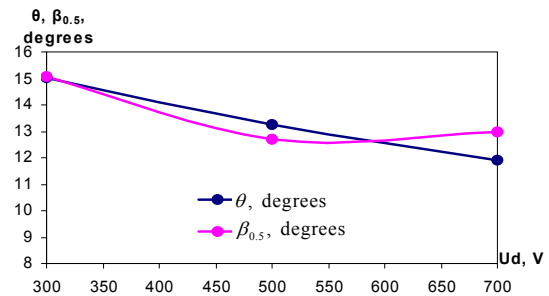


Figure 16. Dependences of the θ and $\beta_{0.5}$ magnitudes on the discharge voltage.

III. Conclusion

As it was shown in the given paper the trend of "narrowing" of the SPT plume with increase of the discharge voltage till at least 700 V and increase of the mass flow rate from low level till nominal values for the SPT "standard" discharge voltages (300-350) V is general one for thrusters of different design and sizes. This trend qualitatively could be explained by the corresponding changes in the local plasma parameters distributions what could be reduced to the shift of the accelerating layer to the thruster exit and reduction of its thickness. Finally these changes are improving the ion flow focusing within the accelerating channel.

Besides it is shown that combined measurements of thruster integral parameters and plume characteristics allows estimation of the doubly charged ions fraction and factors reflecting influence of the mass utilization efficiency, plume divergence, spread of ions in velocities and other loss factors on thrust efficiency.

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