Investigation of the SPT operation and discharge chamber wall erosion rate under increased discharge voltages

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Abstract: **New results of the thruster operation specifics study under operation modes with increased discharge voltages and moderate discharge power are represented in the given paper. Particularly results of the following studies are considered:**

- characterization of the standard PPS1350 model under different operation modes including that ones with increased discharge voltages to clarify reasons of the performance degradation with increase of the discharge voltage and simultaneous reduction of the mass flow rate;

-The SPT-100 type laboratory model erosion test and local plasma parameter measurements along its external discharge chamber wall by the near wall probes.

Obtained results are represented in the given paper.

I. Introduction

Nowadays it is reasonable to develop SPT with increased specific impulse. It is known also that the most simple way to increase specific impulse is to increase discharge voltage and to reduce mass flow rate in order to maintain moderate discharge power density under fixed thruster sizes. Therefore it is interesting to study thruster operation under such operation modes and some studies were already done earlier. [1-6] Obtained results show that under the mentioned operation modes and fixed power thrust efficiency is typically reduced relative to the possible one with increase of the discharge voltage. “The possible one” means the level which is demonstrated under increased discharge voltages and moderate mass flow rate, if one neglect the necessity to limit discharge power in order to obtain large enough life time. And it is important to clarify the reasons of the mentioned trend. Taking this into account the following studies were made:

- characterization of the standard PPS1350 model under different operation modes with increased discharge voltages including the registration of its thermal state and measurements of the current of ions leaving thruster;

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-the SPT-100 type laboratory model performance and erosion tests combined with the local plasma parameter measurements along its external discharge chamber wall by the near wall probes;

These studies were fulfilled within the frames of the CNES-INTAS projects ##03-53- 3358, 06-1000024-8851 and internal Russian projects including the RFBR one #05-08-011411 and the state purchase order 02.445.11.7323. Obtained results are represented below.

II. Some possibilities of the SPT mass utilization efficiency determination.

As was mentioned above under increased discharge voltages and reduced mass flow rates thrust efficiency is typically reduced with increase of the discharge voltage relative to maximum of possible one. As one of the most probable reasons of this trend the reduction of the plasma density inside the accelerating channel and corresponding reduction of the ionization efficiency finally causing the reduction of the mass utilization efficiency was noted. Indeed, there was written already[7] that the plasma density in the so-called ionization zone

$$n_i \approx \frac{I_i}{eV_{iz}S_c} \approx \eta_i \frac{\dot{m}}{MV_{iz}\pi db_c} \, , \qquad (1)$$

where $I_i, V_{iz}, e, \eta_i, \dot{m}, M, S_c = \pi db_c$ are the ion current at the end of the ionization zone, mean ions velocity longitudinal component in the ionization zone, electron charge, mass utilization efficiency (calculated at the exit boundary of the mentioned zone), mass flow rate through the accelerating channel, mass of ion and cross-section of the accelerating channel with the mean diameter d and channel width b_c, respectively.

Then one can obtain that the free pass of atoms before their ionization

$$\lambda_i \approx \frac{V_{az}}{\langle \sigma_i V_e \rangle n_e} \approx \frac{V_{az} V_{iz} M\pi db_c}{\langle \sigma_i V_e \rangle \eta_i \dot{m}} \, , \qquad (2)$$

where $V_{az}, \langle \sigma_i V_e \rangle$ are the atoms velocity longitudinal component and ionization rate factor, respectively.

And under some assumptions one can derive[7] that the λ_i value is to be increased under high discharge voltages and reduction of the mass flow rate due to reduction of the plasma density and atoms ionization probability inside the accelerating channel. Finally this effect have to cause reduction of the thrust efficiency due to reduction of the mass utilization efficiency. In reality situation is complicated enough. Indeed, there are many playing factors determining the ionization efficiency. Particularly one can imagine that atoms velocity in the first approximation is proportional to the root square of the anode or discharge chamber wall temperatures. Then, with increase of the discharge voltage even under fixed power these temperatures are increased due to reduction of the thrust efficiency. The next point is that under increase of the discharge voltage an electrons temperature and ionization rate factor are increased. Concerning the ions velocity one can use different approaches. One of them is to assume that potential difference in the ionization zone is proportional to the discharge voltage. An another option is to assume that this potential difference is more or less constant. To clarify this point one can use the local plasma parameter measurements and some results of such measurements are represented below. Surely the most clear answer can be obtained by the direct measurement of the η_i magnitude for the whole thruster. But this measurement is not a simple one.

One of the mass utilization efficiency measurement difficulties is an existence of the multiply charged ions in the accelerated ion flow. So, even the accurate measurement of the total current of ions exhausting thruster (total ion current) does not allow an accurate enough determination of the η_i value. The problem could be solved, if one measures the multiply charged ions fraction in the whole plasma flow exhausting thruster in parallel with the total ion current measurements. But this is complicated enough task. One of the simplified approaches to overcome this difficulty could be the following. If one assumes that:

1. There are only singly and doubly charged ions in the exhausting thruster plasma flow with the mass flow rates $\dot{m}_{i1}$ and $\dot{m}_{i2}$ for the singly charged and doubly charged ion flows, respectively. Then the total mass flow rate of ions

$$\dot{m}_i \approx \dot{m}_{i1} + \dot{m}_{i2} \qquad (3)$$

Thrust F:

$$F = \dot{m}_a V_z \approx \dot{m}_{i1} V_{i1z} + \dot{m}_{i2} V_{i2z} = \dot{m}_i V_{iz} = \dot{m}_a \eta_i V_{iz} \, , \qquad (4)$$

where $\dot{m}_a$ is the total mass flow rate through the accelerating channel,

$V_z = \frac{F}{\dot{m}_a} = \eta_i V_{iz}$ is the mean plasma flow exhaust velocity longitudinal component,

$\mu_1 = \frac{\dot{m}_{i1}}{\dot{m}_i}, \mu_2 = \frac{\dot{m}_{i2}}{\dot{m}_i}$, $\eta_i = \frac{\dot{m}_i}{\dot{m}_a}$ are the singly charged ions, doubly charged ions mass flow rate fractions and mass utilization efficiency, respectively,

$$\mu_1 + \mu_2 = 1 \tag{5}$$

The current of ions exhausting thruster

$$I_i = \frac{\dot{m}_{i1}}{M} e + \frac{\dot{m}_{i2}}{M} 2e = \frac{\dot{m}_i}{M} e(\mu_1 + 2\mu_2) = \frac{\dot{m}_a}{M} e\eta_i (\mu_1 + 2\mu_2) = I_m \eta_i (1 + \mu_2) \ , \tag{6}$$

where $I_m = \frac{\dot{m}_a}{M} e$.

The losses of the ion velocity longitudinal components are the same for both fractions and the mentioned components can be determined as

$$V_{i1z} \approx \sqrt{\frac{2e(Ud - \Delta U)}{M}}, V_{i2z} \approx \sqrt{2} V_{i1z} \tag{7}$$

Respectively the ions mean velocity longitudinal component

$$V_{iz} = \mu_1 V_{i1z} + \mu_2 V_{i2z} = (\mu_1 + \sqrt{2}\mu_2) Vi1z \ , \tag{8}$$

and

$$V_{i1z} = \sqrt{\frac{2e(U_d - \Delta U)}{M}} = \frac{V_{iz}}{\eta_i (\mu_1 + \mu_2 \sqrt{2})}, \tag{9}$$

where U_d is the discharge voltage, ΔU is the volt-equivalent of all losses, e, M are the electron charge and ion mass, respectively.

One can note that relatively small difference in the ΔU values for the singly and doubly charged ions will not give great errors in the ratio of the corresponding ions velocities in Eq.(7) due to these velocities dependence character on the ΔU values.

Under these assumptions one can obtain expressions for the estimation of the doubly charged ions fraction μ_2 in the exhausting plasma flow and of the mass utilization efficiency:

$$\mu_2 \approx \frac{\frac{I_i}{I_m} \frac{V_{i1z}}{V_z} - 1}{1 - \frac{I_i}{I_m} \frac{V_{i1z}}{V_z} \left(\sqrt{2} - 1 \right)} \ , \tag{10}$$

$$\eta_i \approx \frac{I_i}{I_m (1 + \mu_2)} \ , \tag{11}$$

where $I_m = \frac{\dot{m}_a}{M} e$ is the current equivalent to the mass flow rate through the accelerating channel.

Equations (5,9-11) allows estimation of the $\Delta U, \eta_i, \mu_2$ values, if the thrust, mass flow rate through the a celerating channel and total current of ions exhausting thruster are measured. So, it is useful to realize accurate enough total ion current measurements.

The several methods of the total ion current measurements were used earlier. One of them was the usage of the flat electrostatic probe with negative relative to plasma potential shift and with guard ring[8,9]. This probe could be moved outside the accelerating channel in the plane parallel to the thruster exit plane positioned closely to the thruster exit plane and to measure the ion current distribution along the radial direction [9]. Integrating this distribution it was possible to determine the total ion current crossing the mentioned plane under the mentioned potential shift and to assume that this current correspond to the ion current leaving thruster. In principal one has to add measurements of the ion current leaving thruster through the gap between thruster exit plane and measurement plane but under small distance in between these planes the mentioned current is typically small enough.

The next possibility is to measure the spatial ion current distribution along the "reference" surface surrounding thruster and positioned at large enough distance from the thruster exit. Part of this surface could be semispherical one[10] and it is necessary to determine the ion current distribution along full semisphere and along other surfaces closing "reference" surface, for example, along the part of the thruster exit plane outside thruster exit.

The errors of the ion current determination in these two cases could be caused by the secondary electron emission and "probe ion current" from the secondary plasma (more significant in the second case) what is important under relatively high pressure in the vacuum chamber. Then, the measurement errors depend on the probe design etc.

To reduce the secondary plasma impact on the measurement result it is possible to use the RPA probe with retarding potential of ~20V relative to the plasma potential to avoid penetration of the secondary plasma ions into RPA[10]. In this case some slow ions leaving thruster are lost and the total ion current is underestimated. One can add that RPA is to be calibrated somehow. So, all the mentioned methods of the total ion current measurement are not simple ones and give some uncertainties. Therefore it is interesting to consider other options.

In between these options one can distinguish the possibility to measure the total ion current by large collectors. From the beginning of the SPT studies some of such options were tried[8] and the different targets positioned via thruster exit at a distance not disturbing thruster operation. The most attractive is the possibility to use as a collector the full vacuum chamber because in this case it is not necessary to have any additional parts. To realize this possibility one has to have discharge circuit divided from the vacuum chamber and to measure currents from plasma to the vacuum chamber under different negative its potentials relative to the plume plasma potential. Typically the cathode is used as the second point of the measurement circuit in the considered case. So, one can obtain voltage-current characteristics of the vacuum chamber versus its potential shift relative to cathode similar to the probe characteristics (Fig.1) and can determine the ion current to the chamber as it is done for the general probes.

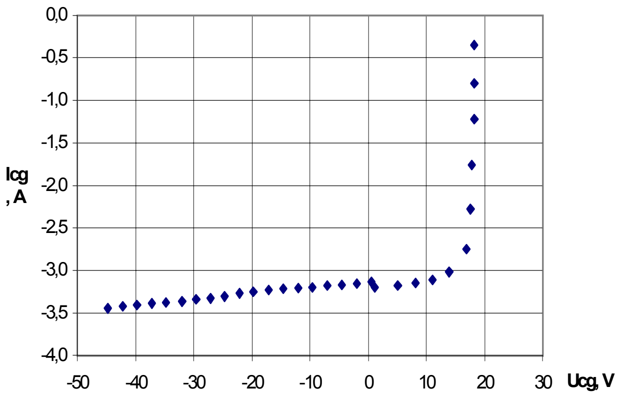


Figure 1. Cathode-vacuum chamber voltage-current characteristics.

The negative potential shift of the vacuum chamber relative to cathode is limited by the discharges appearing under high enough potential difference in between vacuum chamber and cathode. So, one can use low (even zero, see Fig.1) potential difference which is still sufficient to get more or less reliable result of measurement but to avoid appearance of the mentioned discharges. The zero potential difference case is the most simple one because in this case the measurement could be realized only with ammeter that is without additional power supply source. An expected measurement error in this case could be at level of ~5% (see Fig.1). The secondary electron emission current of pure metal surfaces could be also at level of several percents under energy of ions ~300…600 eV [11].

One can add that during the ion current measurement an electron flow from cathode to the vacuum chamber is suppressed and cathode provides only electrons going into discharge chamber that is cathode current is reduced till 20…30 % of its nominal value. Under cathode operation in the so-called "automode" while its thermal state is maintained by discharge between plume plasma and cathode the plasma-cathode potential drop is increased under lowering of the cathode current. Thus, the conditions of the cathode operation and of the whole thruster operation could be changed and it is necessary to use some measures to avoid such changes.

Thus, to use the discussed possibility the internal surfaces of the vacuum chamber are to be clean. If some of them are dirty, the secondary ion-electron emission could be significant and the resistance of their surface layer could be also significant. In the last case the ions coming to these surfaces could be neutralized by electrons from plasma (cathode) that is current of these ions will not be measured by ammeter included in between cathode and vacuum chamber. Taking into account that the SPT plume is cleaning the vacuum chamber wall parts at least within the cone with half angle ~(60-70) degrees it is possible to use combination of the ion collector surrounding thruster outside the mentioned cone and vacuum chamber. This collector is to be removable to clean it before the total ion current measurements. Taking into account that the ion currents going to the vacuum chamber walls outside the mentioned cone are small, one can use for estimations the measurement only with the vacuum chamber. Taking into account that some considered errors have different signs one can expect that the measurement error should be typically less than 10%. Due to simplicity of this method it seems useful for the fast thruster characterization within the wide range of operation modes. Therefore it was used during the PPS-1350 model characterization.

III. Characterization of the PPS-1350 model under different operation modes.

For the given study there was used the PPS-1350 qualification model (QM) developed and manufactured at Fakel (Fig.2). It was modified to avoid breakdowns and failure of insulator dividing gas feeding tube from thruster body and to ensure the possibility of the magnetic field optimization independently on the discharge circuit. To fix the thruster thermal state there were mounted thermocouples T1-T8 (T1 on the magnetic system flange, T2 on the external magnetic pole, T3 and T7 on the discharge chamber keeping element shifted in azimuth direction relative to the axial plane positioned between cathodes by ~90 and ~270 degrees, respectively, T4 and T8 on the internal discharge chamber wall also shifted relative to the mentioned reference plane by 90 and 270 degrees. Such combination of thermocouples allowed determination of the azimuth uniformity of the discharge chamber wall temperature field.

Thruster was tested inside the vacuum chamber with diameter 0.9 m and length of its working part ~3 m. This chamber was equipped by windows allowing to watch thruster view perpendicular to its axis in the exit plane and along direction with off-axis angle ~45 degrees. Vacuum chamber was pumped out by two diffusion pumps ensuring dynamic pressure inside chamber not higher than $\sim 7 \cdot 10^{-5}\,Torr$ (by xenon) under mass flow rate through the accelerating channel ~5 mg/s.

The power supply system consisted of all sources required for thruster feeding.

Thrust measurements were made by device with range of measurements 0…150 mN and accuracy ~2.5 % related to the maximum thrust value.

Anode and cathode were fed by xenon with help of two independent systems. Cathode mass flow rate for all experiments was ~0.35 mg/s. Accuracy of the mass flow measurements was not worse than 3 % related to the maximum value within the measurement range. Electric parameters were measured with accuracy 0.5 % of the maximum value within the measurement range.

Thruster body was insulated from the vacuum chamber walls.

PPS 1350 thruster was qualified for nominal operation mode with discharge voltage Ud=350 V and discharge current Id=3.85 A. During this study thruster was tested within the range of discharge voltages Ud= 200…1000 V with step of 50 V. Then, the upper value of the discharge voltage was limited in order not to exceed 2.5 kW level of discharge power. Additionally under clear thruster overheating it was switched off.

Voltage-current characteristics were determined for the mass flow rate values through anode ensuring discharge current values 5.0, 4.5, 4.0, 3.5, 3.0, 2.5, 2.0 and 1.5 A under Ud=350 V. Measurements were made starting from the maximum anode flow rate. Then it was decreased to get data for new mass flow rate. Under every operation mode the magnetic field optimization was made to get discharge current minimum and there was made measurement of the total ion current leaving thruster by measurement of the cathode-vacuum chamber current.

At the beginning of tests the discharge chamber walls were cleaned. As it was mentioned the voltage-current characteristics were determined under 8 magnitudes of the anode mass flow rates $\dot{m}_a$ (Fig.3) and upper discharge voltage value were chosen at level while discharge power does not exceed 2.5kW. That is why under $\dot{m}_a$ values larger than 3.95 mg/s the discharge voltage values were reduced relative to other cases.

Under lower mass flow rates the discharge voltage was limited by clear appearance of the discharge chamber local overheating. Typically such overheating had appeared at internal discharge chamber wall and due to such overheating for all characteristics the discharge voltage value did not reach 1000V for high enough mass flow rates. So, upper boundary of the possible steady state operation modes (shown in Fig.3 by black solid line) were limited by the discharge voltage values ~600V.

The internal discharge chamber wall temperature measurements had shown that:

- under high temperatures the heating of wall is nonuniform in azimuth direction and temperature difference can reach 200 C (this trend was confirmed also by consideration of the discharge chamber keeping element temperatures T3 and T7, measured in the shifted in azimuth direction points);
- under Ud>500 V the temperature relationship for the points shifted in azimuth becomes opposite to that one under low temperatures.

These data show that under high discharge voltages the optimized magnetic field and respectively the ion flow structure is changed qualitatively.

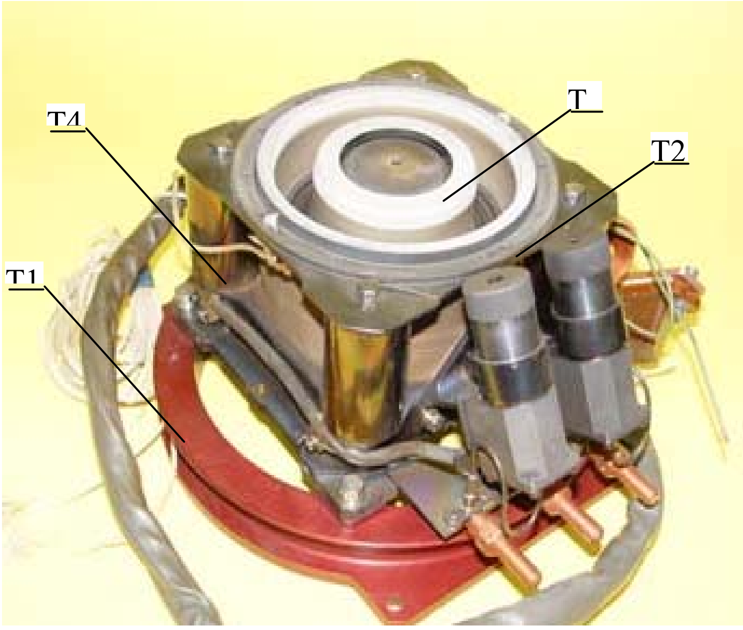


Figure 2. PPS 1350QM general appearance.

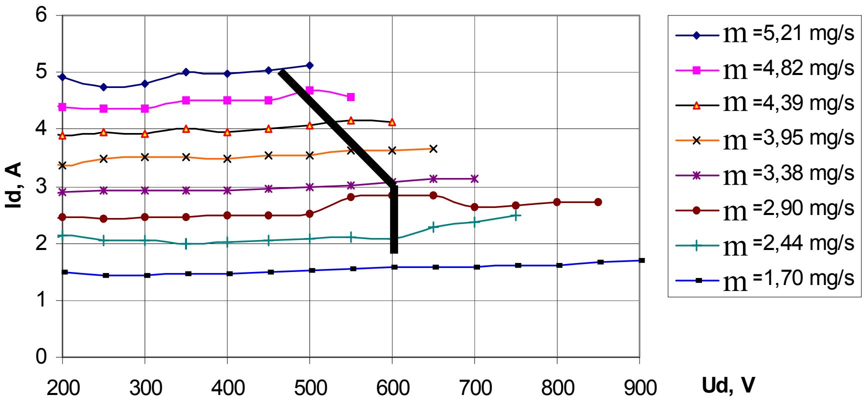


Figure 3. Voltage-current characteristics of the PPS-1350 thruster.

Dependence of the wall temperatures on discharge power (Fig.4) shows that the wall temperature is almost proportional to the discharge power and that temperature level is higher for the low mass flow rates. This is an indication of the significant role of the thermal conductivity in the heat removal from the discharge chamber and of the thermal losses fraction increase with increase of the discharge power and reduction of the mass flow rate. The last part of this conclusion is confirmed by the thrust efficiency dependence on the discharge voltage (Fig.5)

As usual under increase of the discharge voltage thrust is more or less regularly increased but in correspondence with reduction of the thrust efficiency the specific impulse values are lower under the same Ud values for the lower mass flow rates. All specific impulse values are notably lower than that one calculated with usage of the discharge voltage as the accelerating one and assuming full ionization of the flow rate and absence of the multiply charged ions (Fig.6).

Measurements of the discharge current and discharge voltage oscillations (Fig.7 and Fig.8) show that for moderate mass flow rates the discharge current oscillation intensity has higher level and reaches maximum within the discharge voltage range (600-700)V and this, probably, could be connected with the necessity to change of the optimum magnetic field topology and corresponding change of the plasma-wall interaction. The mentioned point is confirmed by the consideration of the magnetization currents ratio required to reach the discharge current minimum. There was found also that the oscillation intensity depend on discharge chamber and anode surfaces cleaning. And it is still difficult to explain such discharge behaviour.

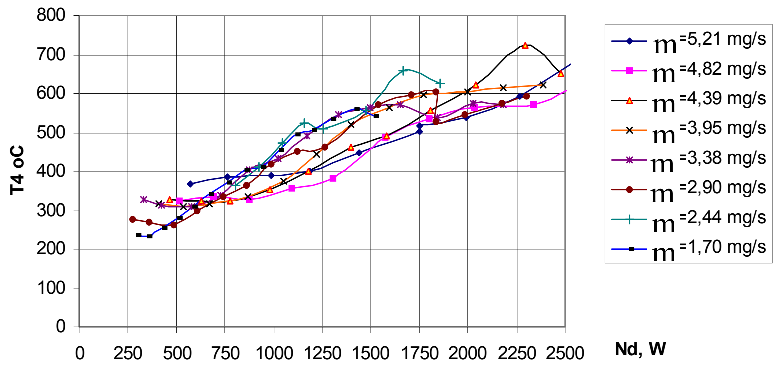


Figure 4. The internal wall temperature in the plane shifted by 90 degrees relative to the reference plane versus discharge power.

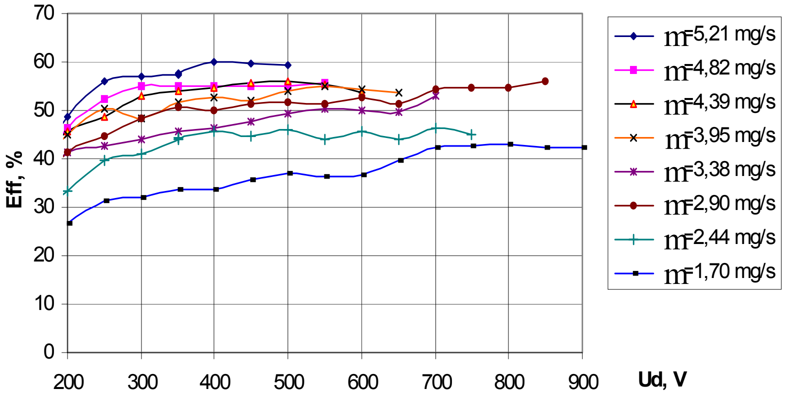


Figure 5. Thrust efficiency versus discharge voltage.

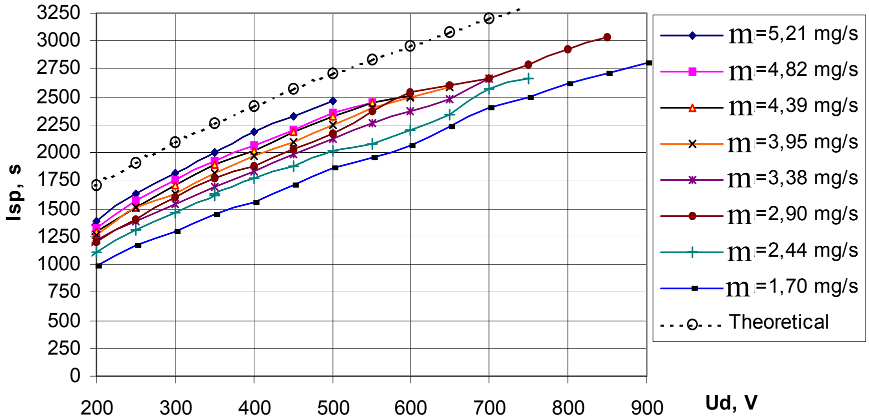


Figure 6. Specific impulse versus discharge voltage.

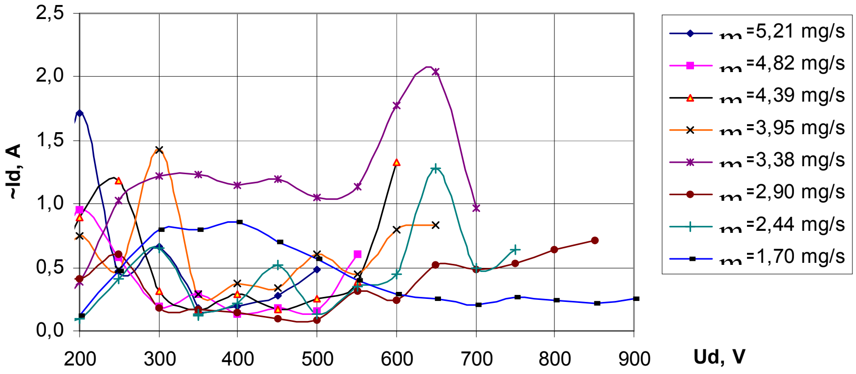


Figure 7. RMS discharge current amplitude versus discharge voltage.

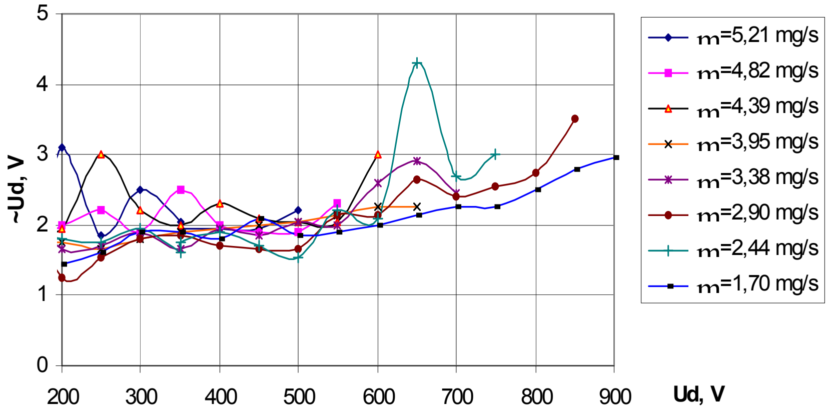


Figure 8. RMS discharge voltage amplitude versus discharge voltage.

Dependence of the ion current (measured with usage of the vacuum chamber as the ion collector) to discharge current ratio on the discharge voltage shows (Fig.9) that the mentioned ratio for the typical mass flow rates reaches 0.75…0.85 what is close to values obtained for such operation modes by other methods [9]. And one can see also that under lowering of the mass flow rates this ratio is reduced.

Partially the ionization efficiency can be estimated by ratio of the ion current to current equivalent to the mass flow rate of propellant through the accelerating channel. This ratio is slightly increased with the discharge voltage increase and is definitely reduced with reduction of the mass flow rate (see Fig.10). If one takes into account the doubly charged ions and uses equations (5,9-11), then one can also obtain that under reduced mass flow rates the mass utilization efficiency is lower (Fig.11). At the same time the doubly charged ion fraction under low mass flow rates is higher (Fig.12). So, obtained data confirm the conclusion that reduction of the mass utilization efficiency is one of the reasons for the reduction of thrust efficiency. As an additional factor one can note an increase of the doubly charged ions fraction.

It is worth to note that obtained data on the doubly charged ions fraction are also close to results obtained by other methods[12].

Consideration of the magnetization currents giving the optimized operation modes shows that variation of these currents is very complicated but generally the total their amp-turns are not increased till the discharge voltage values ~500V (Fig.13) and then at least under moderate and large mass flow rates an internal magnetization current is to be increased significantly with corresponding increase of the internal to external magnetization currents ratio. This is an indication of the magnetic system limited capabilities as a reason for the thrust efficiency reduction under these operation modes. But under low mass flow rates one has to find other explanations.

The next possible reason of the thrust efficiency reduction under reduced mass flow rates is an increase of the power losses on the walls. Partially this possibility was confirmed by the results of the erosion tests to determine the erosion traces length. These tests were made under different operation modes each with duration ~4 hours and the erosion traces length on discharge chamber walls were measured. Before each such test cleaning of the discharge chamber walls was made. Obtained results are represented in the Table 1. They show that these lengths are increased with reduction of the mass flow rate and increase of the discharge voltage at least.

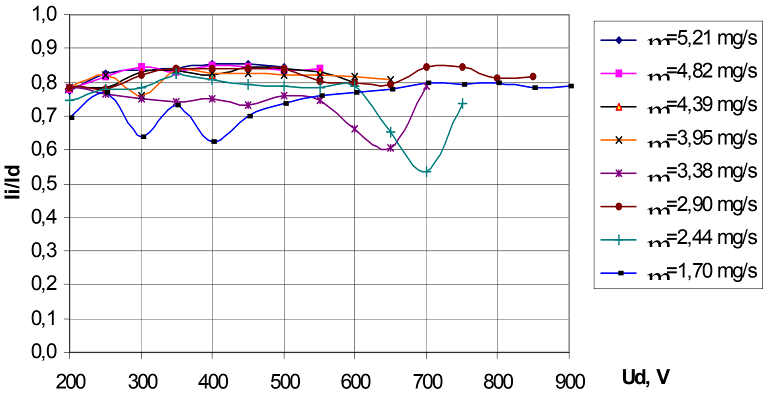


Figure 9. The ion current to discharge current ratio versus discharge voltage.

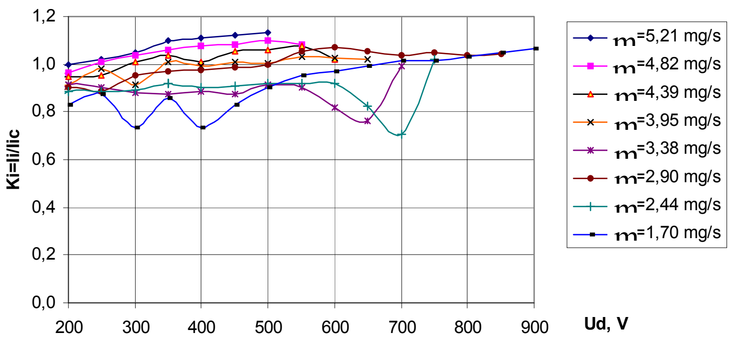


Figure 10. The total ion current to the current equivalent to mass flow rate ratio versus discharge voltage.

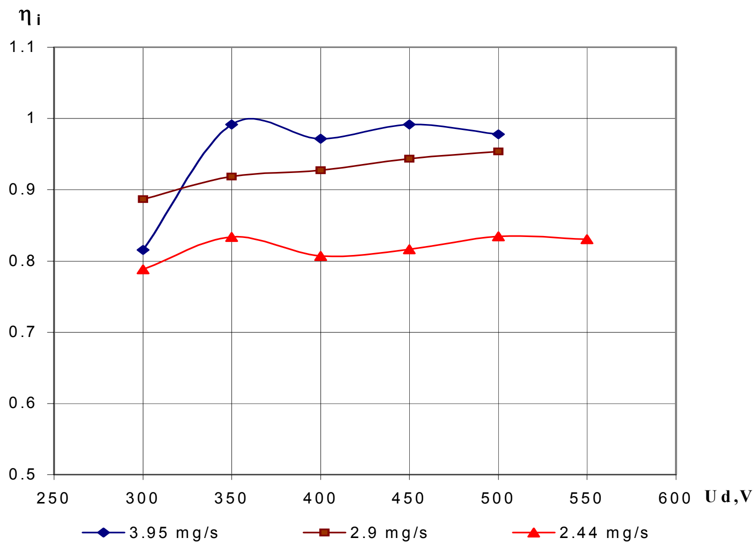


Figure 11. Dependence of the mass utilization efficiency on the discharge voltage.

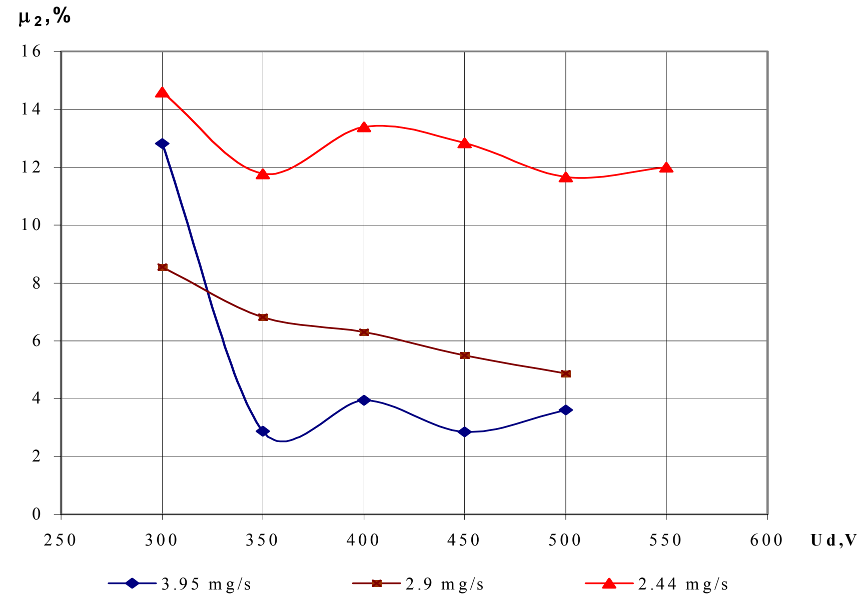


Figure 12. The doubly charged ions fraction versus discharge voltage.

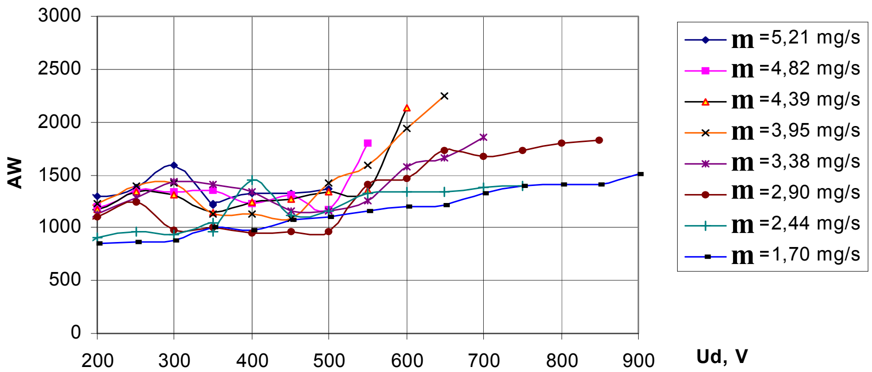


Table 1. The erosion traces length on the walls.

Operation mode	Length of erosion traces, mm	
	External wall	Internal wall
Id=3,85A, Ud=350 V	6,31	6,00
Id=2,00 A, Ud=350 V	8,30	7,28
Id=2,00 A, Ud=600 V	9,05	11,0
Id=5,00 A, Ud=350 V	6,31	7,38

Summing obtained results one can note that reduction of thrust efficiency under increased discharge voltages and reduced mass flow rates could be caused by complex of factors: reduction of the mass utilization efficiency, increase of the doubly charged ions fraction and by an increase of power losses on the walls. An additional data on the discussed topics were obtained during SPT -100 laboratory model tests represented in the next part.

IV. Results of the SPT-100 laboratory model erosion test and local plasma parameter measurements.

As was mentioned an additional information on thruster operation under increased discharge voltages and reduced mass flow rates could be obtained by the erosion tests and local plasma parameter measurements. Therefore one of the erosion tests was made with usage of the SPT-100 type laboratory model under its operation with discharge voltage ~700V and mass flow rate ~2.0 mg/s ensuring the discharge power ~1500W. It is necessary to note that the PPS -1350 and SPT-100 thruster models have very close magnetic system and accelerating channel configurations and sizes. Therefore results obtained for these models could be compared without significant corrections.

Erosion test was made in the vacuum chamber of 2m in diameter and 6m in length pumped out by two diffusion pups ensuring dynamic pressure $\sim 5 \cdot 10^{-5}\, Torr$ (by Xe). So, the test conditions were very close to that one described in the part 2. Similar characteristics had also the measurement systems.

At the beginning of test the discharge chamber wall profiles were measured. Then, after 50 hours and after 100hours of thruster operation they were measured again. As result it was possible to estimate the discharge chamber walls erosion rates and to compare them with existing data for the nominal operation modes of the SPT-100 and PPS -1350 models.

Variation of the performance data during this test was not significant (Fig.14-16) and as a whole their level was typical for operation with increased discharge voltage and reduced mass flow rate.

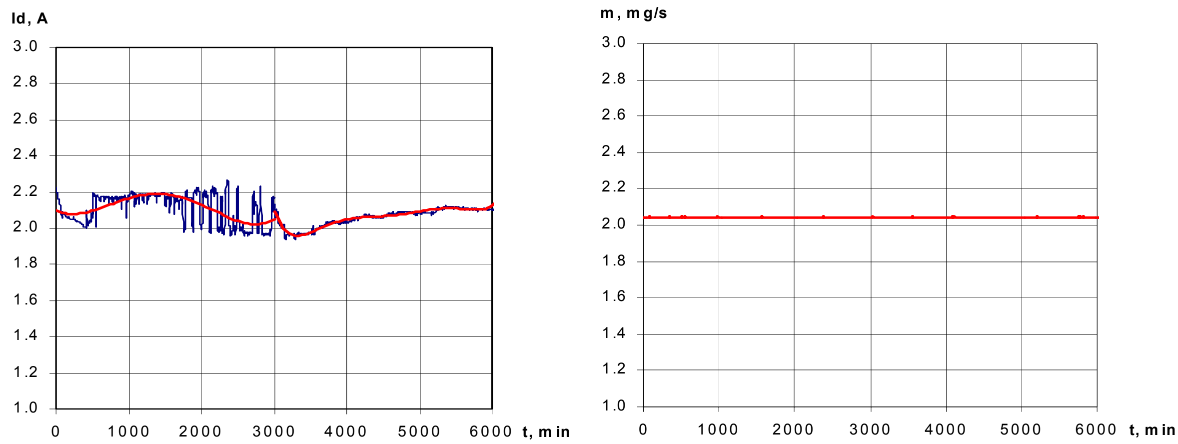


Figure 14.The discharge current and mass flow rate through the accelerating channel versus operation time.

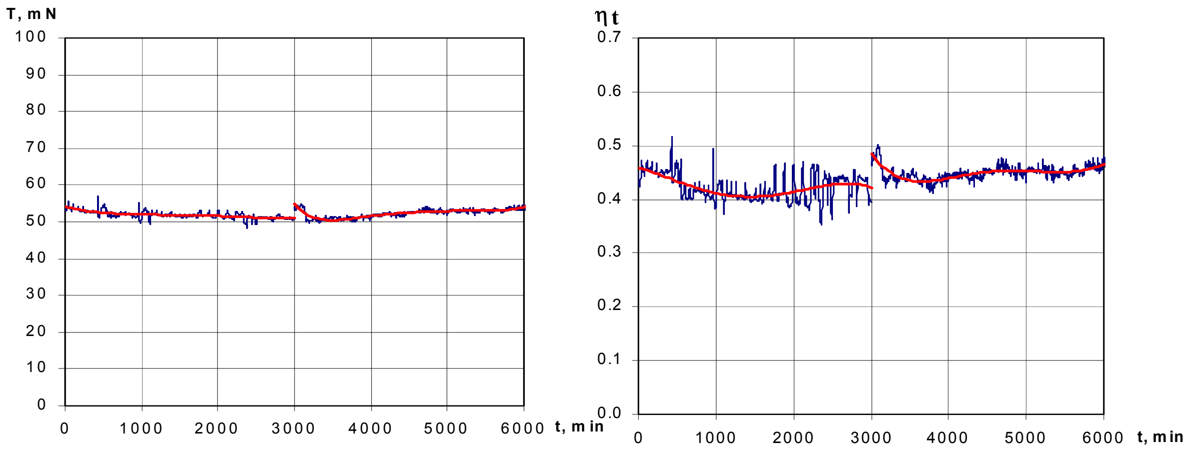
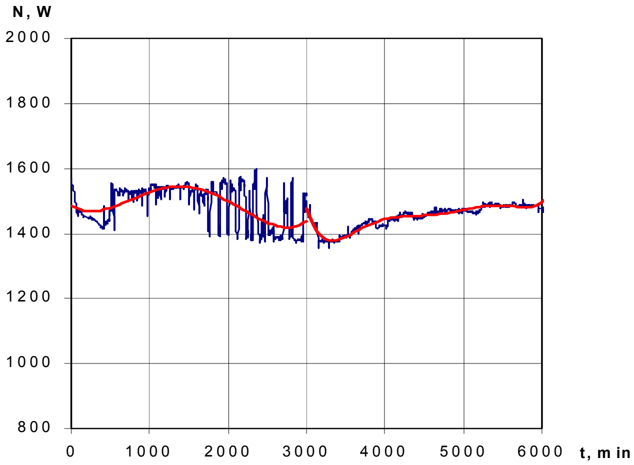


Figure 15. Thrust and thrust efficiency versus operation time.



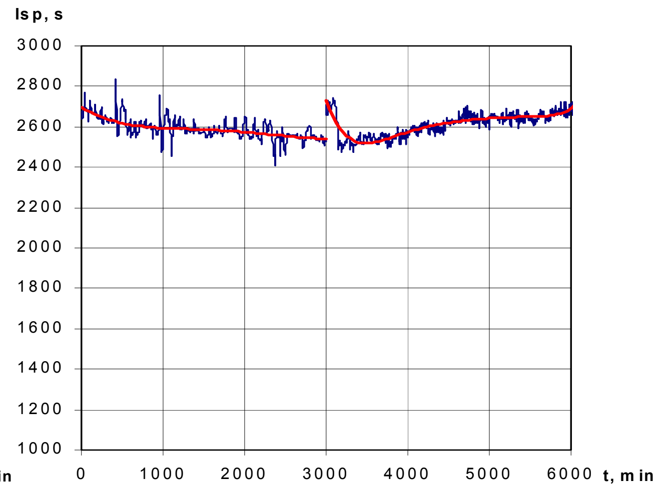


Figure 16. The discharge power and specific impulse versus operation time.

Concerning the specific features of the erosion data one can note the following:

1. Length of the eroded zones are larger than under nominal operation modes of the SPT-100 or PPS-1350 thrusters. Indeed they were ~15mm (Fig.17) while in the SPT-100 case they were at level of 10mm[13] (Fig.18)

2. The maximum erosion rates for both walls realized at the discharge chamber exit was higher by ~1.5 times. Than in the SPT-100 case. Indeed, the maximum change of the wall thickness after 100hours of thrusters operation was ~1.5mm for the external wall and ~1.9mm for the internal wall (see Fig.17) while in the SPT-100 case such level of the wall thickness change was reached after ~160 hours (see Fig.18).

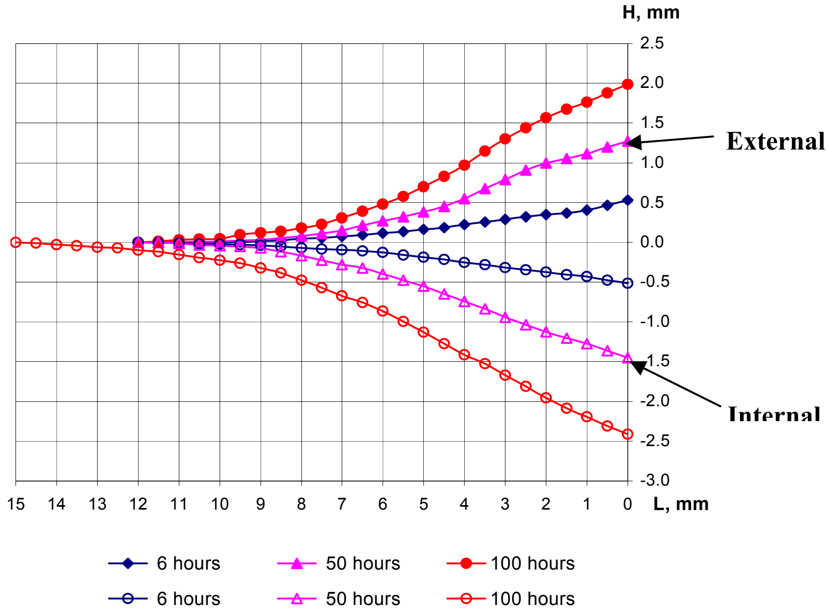


Figure 18. The SPT-100 laboratory model discharge chamber wall profiles.

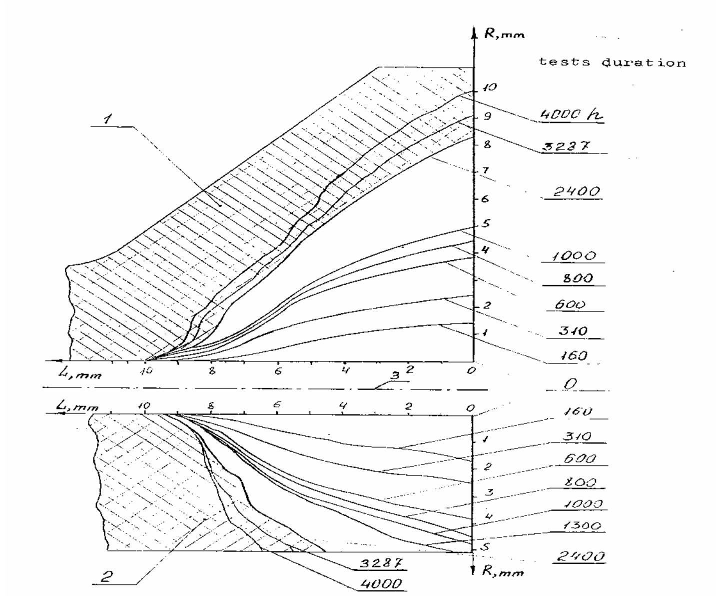


Figure18. SPT-100 channel walls wear profiles during 4000-hour testing process
1-internal wall; 2-external wall ; 3-channel medium diameter line.

Thus, an increase of the erosion traces indicates extension of the accelerating layer into anode direction and possible increase of the ions and power losses on the discharge chamber walls. Some additional information on this topic are given by the local plasma parameter measurements realized by the near wall probes. They allows obtaining of the plasma φ_{pl} and probe floating φ_o potentials, density j_i of the ion current to the discharge chamber wall and of the electrons temperature kT_e (in energy units) distributions along the accelerating channel. Comparison of the obtained data for the discharge voltage values 300V and 700V shows that:

-plasma potential drop in between channel cross-sections at distances from the channel exit 15mm and 10mm (Fig.19) is notably increased and this potential difference has to exceed the sputtering threshold under the mentioned distances larger than 10mm;

-the difference in between plasma and probe floating potentials is also increased (see Fig.19).

The last factor is in correspondence with the electron temperature increase in the near anode zone under increased discharge voltage especially under low mass flow rate (Fig. 20). Concerning the erosion one can note that both factors have to change position of the erosion zone.

Results of the ion current measurements show that under increased discharge voltage reduction of the mass flow rate causes shift of the ion current maximum also into anode direction (**Fig.21**). This an indication of the corresponding shift of the “ionization zone” which has to cause an increase of the ions and power losses on the discharge chamber walls. This shift is causing the mass utilization efficiency and thrust efficiency reduction due to increase of the ions and power losses on walls. Estimation of these losses with help of the methodology used earlier [13] shows that power release on the external wall is increased by ~80W.

An additional reduction of the thrust efficiency should be caused also by an increase of the electron temperature in the near anode zone and by increase of energy delivered to anode by electrons flow. Unfortunately the accuracy of measurements does not allow to close the full energy balance. But these results show clear trends which could be summed as follows: reduction of thrust efficiency under increase of the discharge voltage with simultaneous reduction of the mass flow rate is caused by reduction of the mass utilization efficiency, by an increase of the doubly charged ions fraction and power losses on the walls connected with the shift the ionization zone and of the accelerating layer extension into the anode direction as well as by an increase of the energy delivered by electrons flow to anode

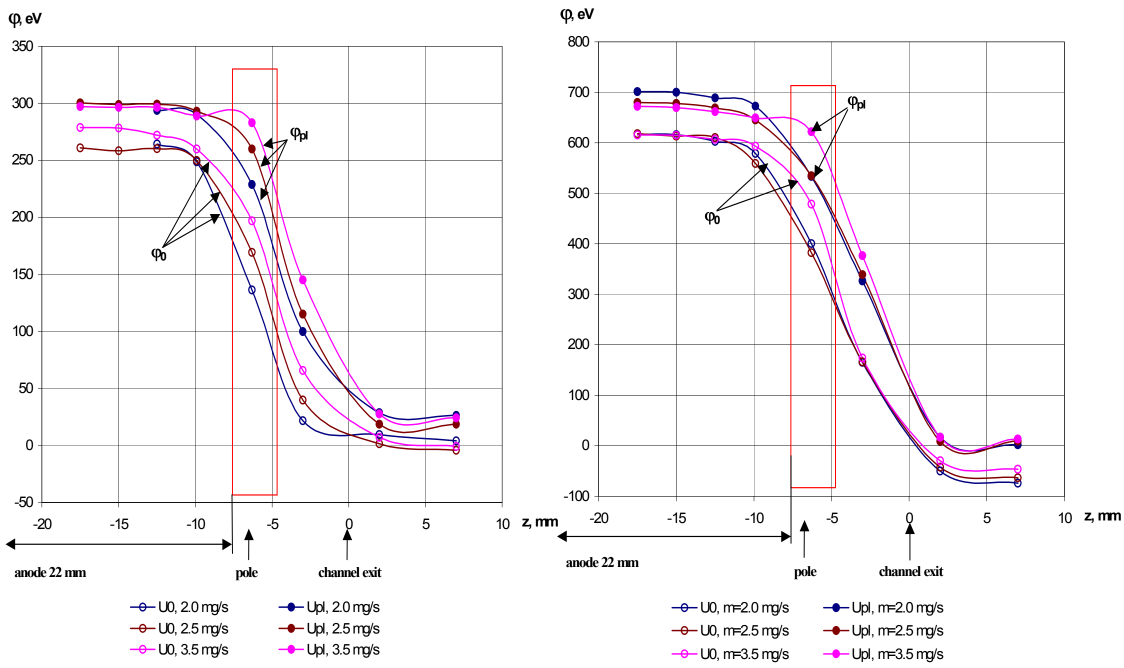


Figure19. Plasma and probe potentials distributions along the accelerating channel.

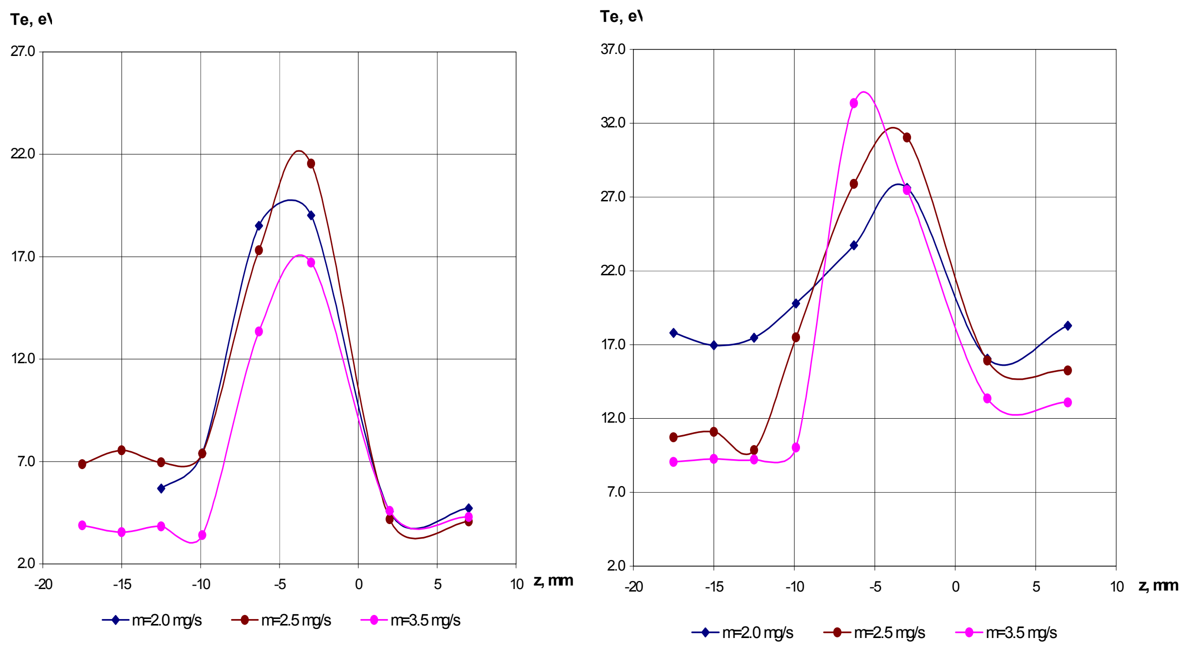


Figure 20. The electron temperature distributions along the accelerating channel

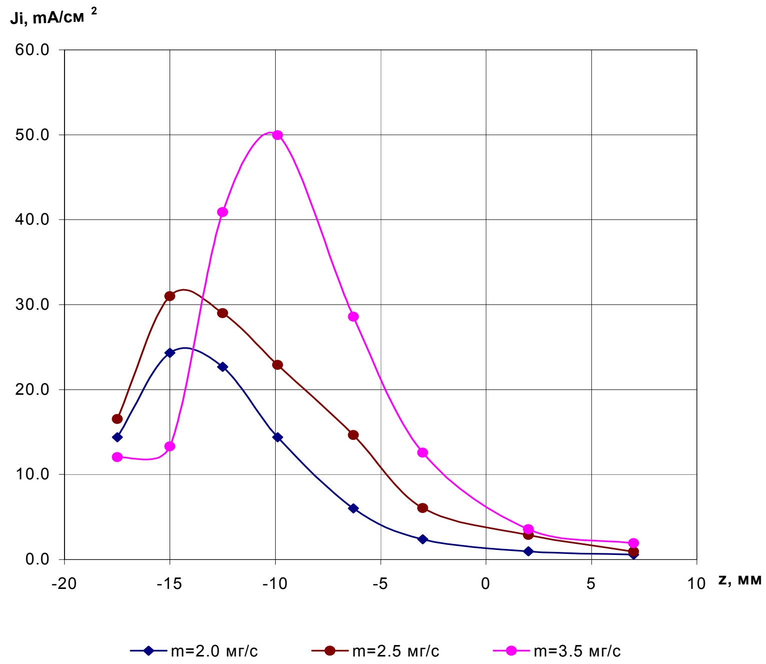


Fig.21. The ion current distributions along the accelerating channel under discharge voltage ~700V

V. Conclusion.

As a whole obtained data show that reduction of the "standard" SPT's thrust efficiency under increase of the discharge voltage relative to the possible maximum is explained not only by the reduction of the mass utilization efficiency, but also by increase of the doubly charged ions fraction and power losses on the discharge chamber walls and energy delivered by the electrons flow to anode.

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