

Investigation of the Local Plasma Parameter Distributions in the SPT Accelerating Channel Under Increased Discharge Voltages

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Abstract: Integral and local plasma parameter distributions inside the accelerating channel of the PPS-1350 type stationary plasma thruster (SPT) laboratory model were determined with usage of the near wall probes under several operation modes with increased till ~700 V discharge voltages. These data allow estimation of the energy release on the discharge chamber walls due to ions impingement with them. Obtained data are compared with results of the mentioned energy release by study of the discharge chamber wall thermal state variation under thruster on/off switchings and with data on the walls erosion.

I. Introduction

As it is well known in spite of the great enough experience of the stationary plasma thruster (SPT) investigation, development and application there are some open questions on physics of its operation. One of them is the question on the energy release due to the plasma-wall interaction inside the accelerating channel. This energy release is great enough what is confirmed by the fact of significant wall erosion and many data confirm that this erosion is connected with the accelerated ions impingement with walls. In principle using the erosion and wall material sputtering yield data one can estimate the mentioned energy release. But the accelerated ions impinge walls under different unknown angles and dependence of the sputtering yield on these angles is significant. Therefore accuracy of such estimation cannot be high. Moreover the wall erosion is significant only at the thruster exit while plasma interacts with walls in the whole channel. This plasma-wall

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interaction causes energy losses and has impact on the energy balance for the whole discharge determining such its characteristics as effective ion production cost, thrust efficiency etc. Therefore it is interesting to continue study of the mentioned plasma-wall interaction characteristics. In particular, it is interesting to study the possible energy release due to the ions impingement with walls under different operation modes including that ones with increased voltages. One of the possible approaches to such study is represented in the paper. This work was fulfilled at RIAME in co-operation with Snecma Moteurs. Some results were obtained by RIAME within the frames of the CNES-INTAS project # 03-53-3358.

II. Investigation Methodology

The PPS-1350 type thruster laboratory model was used for the given study. External discharge chamber wall of this model was equipped by the near wall probes (Fig. 1) as in other cases of such studies¹. The chosen probe sizes and positions do not disturb integral thruster characteristics significantly.

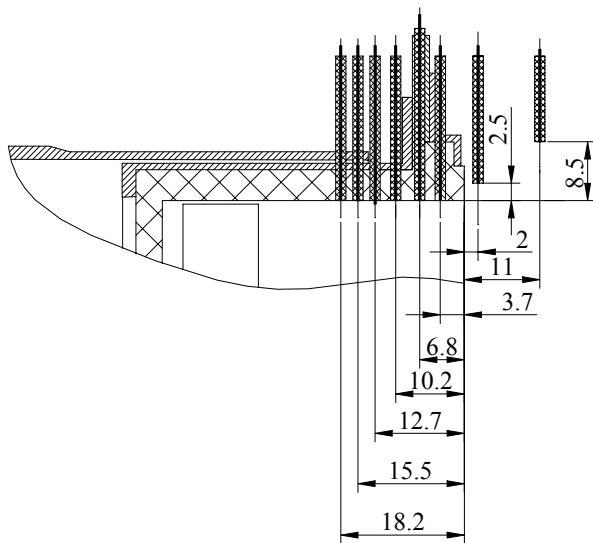


Figure 1. Probe Position Schematics.

For experiments thruster model was installed on thrust stand inside the vacuum chamber of 2 m in diameter and 6m in length pumped out by two diffusion pumps ensuring dynamic pressure inside chamber not exceeding 5×10^{-5} Torr by xenon under its mass flow rate ~ 5 mg/s. Accuracy of thrust measurements was $\sim 2\%$ under thrust level ~ 100 mN.

Two independent Xenon feeding lines fed thruster model with standard MKS type flow controllers. Error of measurements for the mass flow through the accelerating channel was estimated as $\sim 4\%$ and through cathode – as $\sim 10\%$.

Discharge voltage and current as well as the magnetization currents were measured with accuracy $\sim 1\%$.

Thruster integral and local plasma parameters were determined without thruster dismounting from the thrust stand. The local plasma parameter measurements were done after stabilization of the chosen operation mode at least during ~ 1 hour

while there were done the probe surfaces cleaning by application of the negative potential shift relative to the local plasma potential. Then, there were determined the probe voltage-current characteristics of each probe and they were recorded in computer memory. Probe potential variation was realized during 0.2 s.

To reduce oscillations impact on the probe characteristics the special unit was used to suppress the coincide noises. With this unit there was possible to get acceptable probe characteristics which were processed with usage of standard procedures for determination of probe floating potential ϕ_{fl} , ion current J_i to the probe (under its floating potential) and for estimation of an electron temperature T_e , plasma potential ϕ_{pl} and plasma concentration with usage of electron current value under probe potential equal to plasma potential and estimated electron temperature value. It is supposed that probe-floating potential is close to the local discharge chamber wall potential and that probe ion current density is close to the ion current density from plasma to the wall surface. Having these data one can estimate the local energy density carried by ion flow to surface as

$$q_i \approx j_{iw} \Delta \phi \approx j_{iw} (\bar{\phi} - \phi_w), \quad (1)$$

where j_{iw} is the local ion current density to the probe (wall) surface,

$\bar{\phi}$, ϕ_w are the mean plasma potential in «ionization zone» and local wall potential values.

It is known that plasma potential in the «ionization zone» is changed slowly. Therefore one can use for estimation of $\bar{\phi}$ plasma potential values measured by near wall probe in «ionization zone».

Due to ion neutralization at the wall surface there is released an additional energy

$$\varepsilon_n = e\Phi_i + \frac{3}{2}kT_e, \quad (2)$$

where e, Φ_i, kT_e are the electron charge, potential of the atom ionization and electron temperature in energy units. So, the total energy release density due to the ions impingement with walls and their neutralization was estimated as

$$q_w \approx j_{iw} \left[\alpha(\bar{\varphi} - \varphi_w) + \Phi_i + \frac{3kT_e}{2e} \right], \quad (3)$$

where α is the ion energy accommodation factor.

Thus, measuring the local plasma parameters at walls one can estimate energy release delivered by ions and electrons to wall. The main difficulties under such approach are connected with determination of the ion energy accommodation factor as well as determination of $\bar{\varphi}$ and the electron temperature values. Therefore it is to be useful to find other possibilities to estimate this energy release. One of such possibilities is to use data on the wall temperature variation after thruster on/off switchings. Indeed, if one measures the exit wall part temperature, then one can write that its temperature variation can be roughly described by expression

$$C \frac{dT_w}{dt} \approx Q - S_1 \sigma \mathcal{E} \left[\left(\frac{T_w}{100} \right)^4 - \left(\frac{T_{01}}{100} \right)^4 \right] - S_2 \frac{\lambda}{L} (T_w - T_{02}), \quad (4)$$

where T_w, T_{01} and T_{02} are the temperature of the specified wall part, temperature of surrounding this part elements determining the radiation heat exchange between them and temperature of elements connected with the specified wall part determining the conductive heat exchange,

Q and C are the heat (power) release on the wall surface after thruster switching on and the thermal capacity of the specified wall part,

S_1 and S_2 are the surface areas determining heat removal from the specified wall part by radiation and heat conduction,

$\sigma \mathcal{E}$ is the effective emissivity of the specified wall part surface,

λ, L are the thermal conductivity of elements connected with the specified wall part and characteristic their length, respectively.

At the beginning of heating the radiation member in equation (4) is small. Therefore this equation can be reduced to the following:

$$C \frac{dT_w}{dt} \approx Q - S_2 \frac{\lambda}{L} (T_w - T_{02}) = Q - K_\lambda (T_w - T_{02}) \quad (5)$$

Solution of this equation is

$$T_w \approx T_{02} + \frac{Q}{K_\lambda} - \frac{Q}{K_\lambda} e^{-\frac{K_\lambda}{C} \tau} = T_{02} + \frac{Q}{K_\lambda} \left(1 - e^{-\frac{K_\lambda}{C} \tau} \right) \quad (6)$$

So, the characteristic time of heating is $t_0 = \frac{C}{K_\lambda}$ and, if $t \ll t_0$, then

$$\left. \frac{dT_w}{dt} \right|_{t \sim 0} \approx \frac{Q}{C} e^{-\frac{K_\lambda}{C} \tau} \quad (7)$$

So, if thruster is switched on from the state with the same temperatures of all its elements, then at the beginning of its operation

$$\left. \frac{dT_w}{dt} \right|_{t \sim 0} \approx \frac{Q}{C} \quad (8)$$

and, if somebody knows the thermal capacity of the specified wall part, one can determine power release on this part of discharge chamber fixing its temperature variation in time just after beginning of thruster operation.

Another option is to estimate energy release after thruster switching off measuring the temperature variation just after thruster switching off. In this case due to thermal inertia of thruster elements the temperature variation

is determined mainly by transition Q value to zero. Indeed, under equilibrium thruster thermal state during its steady state operation

$$C \frac{dT_w}{dt} \approx 0 \quad (9)$$

and

$$Q = S_1 \sigma \epsilon \left[\left(\frac{T_w}{100} \right)^4 - \left(\frac{T_{s1}}{100} \right)^4 \right] - S_2 \frac{\lambda}{L} (T_w - T_{s2}), \quad (10)$$

where T_{s1} and T_{s2} are the temperature of elements surrounding the specified wall part and temperature of elements connected with this part, respectively (under steady state thruster operation).

So, just after thruster switching off the rate of cooling is determined by the right part of expression (10) equal to Q and therefore

$$\left. \frac{dT_w}{dt} \right|_{t \sim 0} \approx -\frac{Q}{C} \quad (11)$$

Thus, measuring the temperature variation just after thruster switching off and knowing the wall part thermal capacity one can estimate Q value.

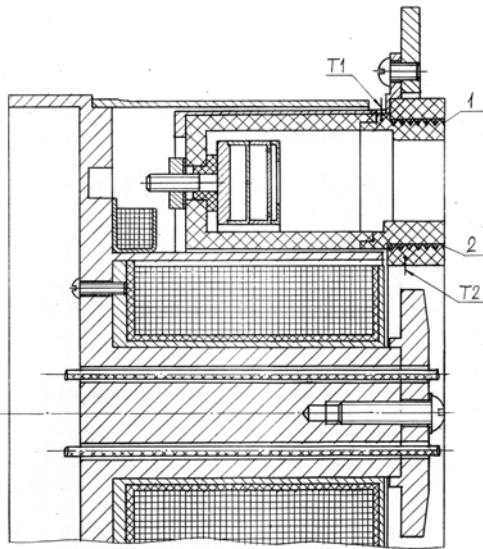


Figure 2. PPS-1350 Laboratory Model With Heaters of the Discharge Chamber Walls and Thermocouples.

walls and it was possible to control wall temperatures during their heating by these heaters. In particular there were obtained the temperature dependencies under external wall heating by power ~300 W and internal wall heating by power ~260 W (Fig. 3).

As one can see the initial temperature dependence could be considered as close to linear one. Therefore it is possible to estimate the rates of the initial temperature increase. Such determination gives under mentioned heating powers the rates of heating for the internal wall ~ 2.94 degrees per second (deg/s) and for the external wall ~ 2.27 deg/s. Respectively, with usage of the expression (8) it

This means that deriving the temperature dependence on time one can find the $\frac{Q}{C}$ ratio or to determine one of these magnitudes, if there is information on another one. In this connection it is interesting to note that earlier there were made by RIAME for Snecma some temperature measurements² with special PPS-1350 laboratory model (Fig. 2). This model had heaters inserted inside exit parts of these

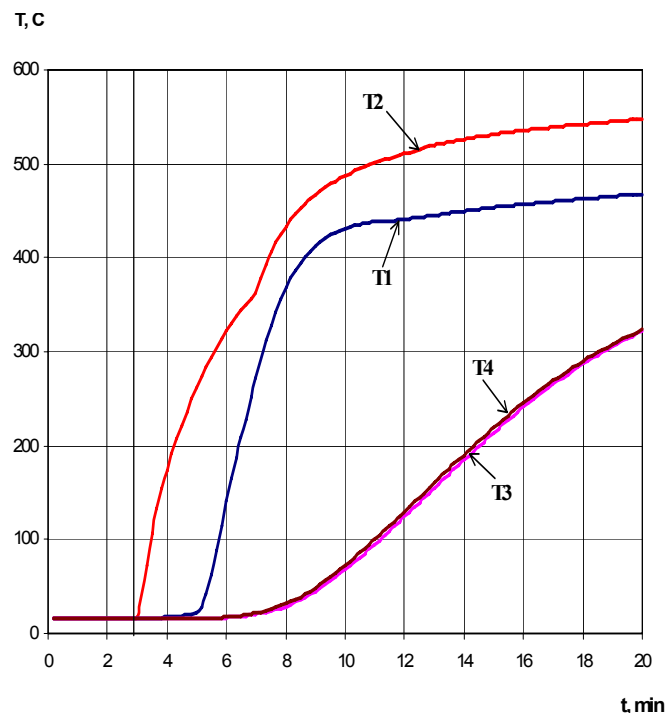


Figure 3. Initial Thruster Elements Variation in Time During Preheating (T_1 is External Wall Temperature; T_2 is Internal Wall Temperature; T_3 , T_4 are Anode Temperatures).

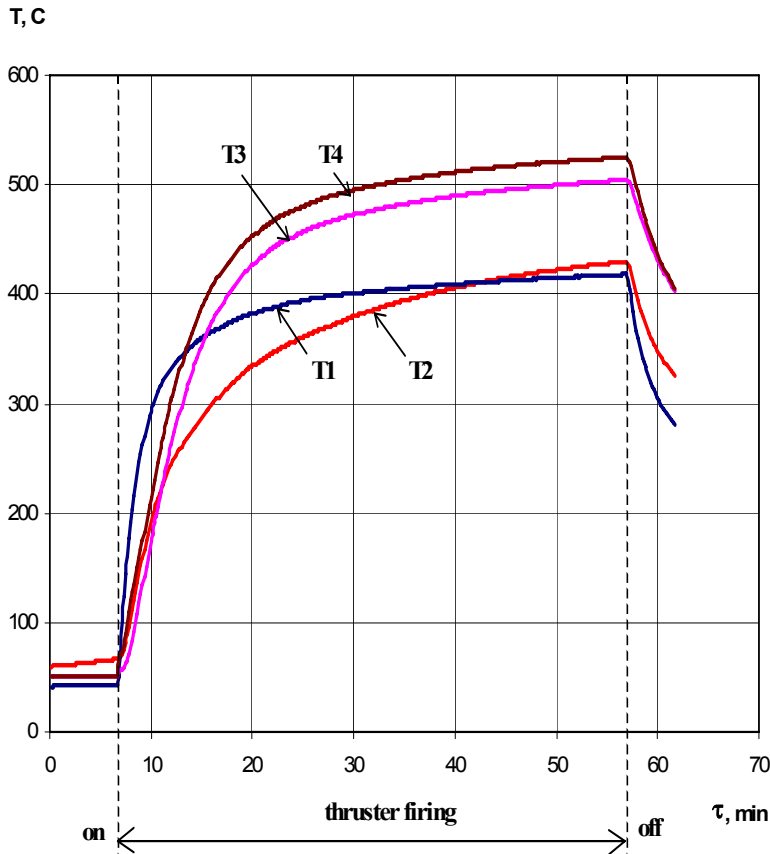


Figure 4. Temperature variation after PPS-1350 laboratory model switching on (T_1 is internal wall temperature; T_2 is external wall temperature; T_3, T_4 are anode temperatures).

The total power release on both walls just after “fresh” thruster switching on was ~ 340 W while just before thruster switching off it was ~ 205 W, that is total power losses on the walls are within (14-23)% of discharge power and at the end of cycle the level of losses is lower than at the beginning of cycle what is confirmed also by thrust efficiency determination for the considered case of “fresh” thruster. For further consideration it is important that the represented above data give level of wall losses, which can be compared with data obtained with usage of the local plasma parameter measurements.

Table 1. Power release on the discharge chamber wall exit parts, W

Time Moment	Power Release, W
On external wall after switching on	~ 105
On external wall before thruster switching off	~ 90
On internal wall after thruster switching on	~ 234
On internal wall before thruster switching off	~ 114

III. Some Results of the Local Plasma Parameter Measurements

Results of the local plasma parameter determination with usage of the described above near wall probes are typical for SPT, namely: reduction of plasma and probe floating potentials under nominal operation mode is realized along the exit part of the external wall at distances 7...8 mm from the channel exit (Fig. 5) that is the accelerating layer is positioned near the channel exit.

The ion current distribution has maximum just at the beginning of the accelerating layer (Fig.6).

was possible to estimate the walls thermal capacities which were found as $C_2 \approx 88 \text{ Joules/deg}$ for the internal wall and $C_1 \approx 134 \text{ Joules/deg}$ for the external wall. Then, for the same thruster model design the temperature dependencies on time were determined during thruster switching on, its operation during 50 minutes with nominal operation mode parameters (discharge voltage 350 V and discharge current ~ 4.28 A) and during some time after thruster switching off for different thruster model states². For, example, for the «fresh» (being in atmosphere) thruster the corresponding temperature variation curves are represented in Fig. 4.

Using these data and expressions (8) and (11) one can estimate the energy release on the walls just after thruster switching on and just before thruster switching off. Obtained data are represented in the Table 1.

It was found also that power release is different for the outgassed and «fresh» thrusters.

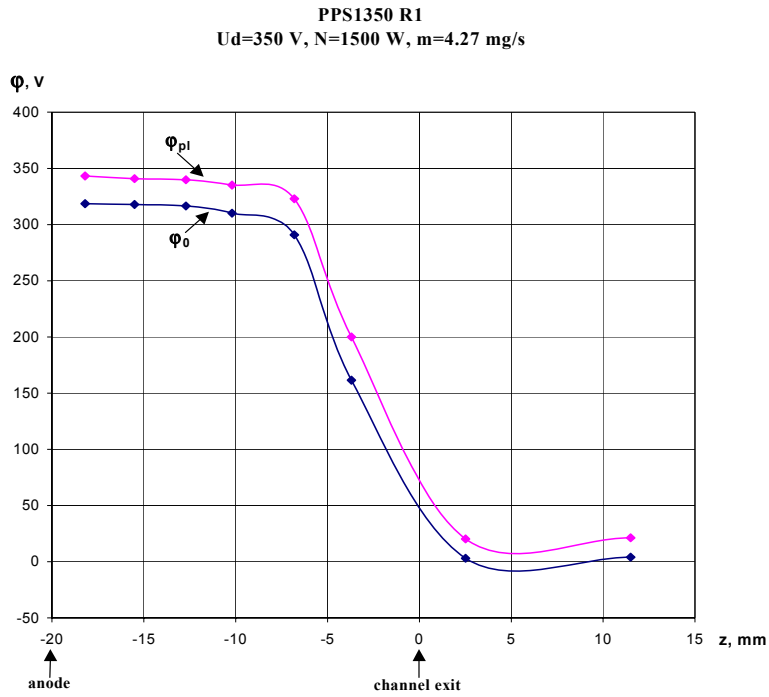


Figure 5. Plasma and Probe Floating Potentials Distributions Along the External Wall

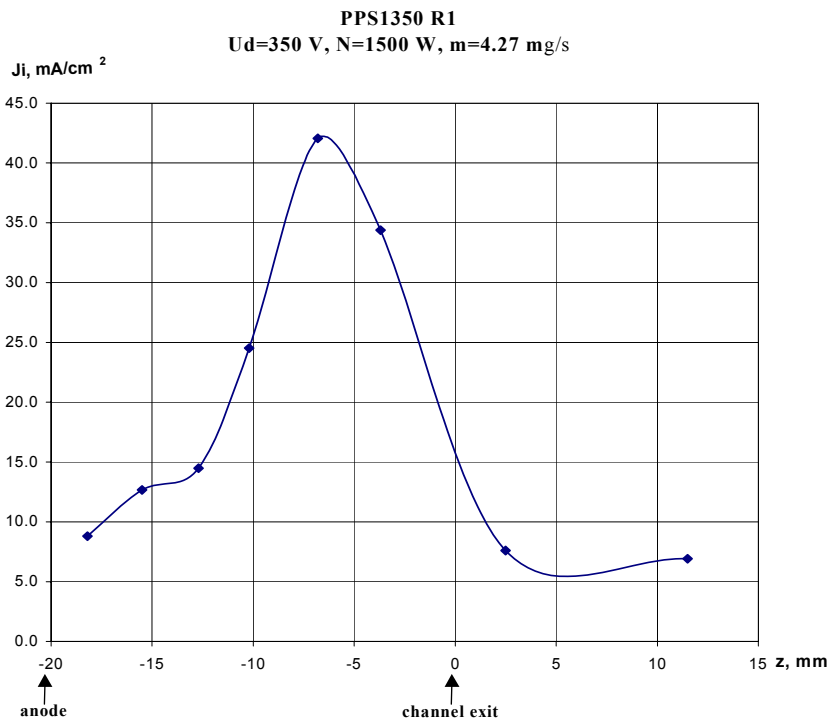


Figure 6. The Ion Current Density Distribution Along the External Channel Wall

As was mentioned above for estimation of the possible total energy release per single ion getting wall there was used the magnitude $\Delta\phi_0 + = \Delta\phi_0 + \phi_i + \frac{3kT_e}{2e}$, where the $\Delta\phi_0 = \phi_{pl} - \phi_o$. Obtained data including the electrons temperature data (Fig. 7) show that both these magnitudes are increased rapidly from the ionization zone till channel exit (Fig. 8).

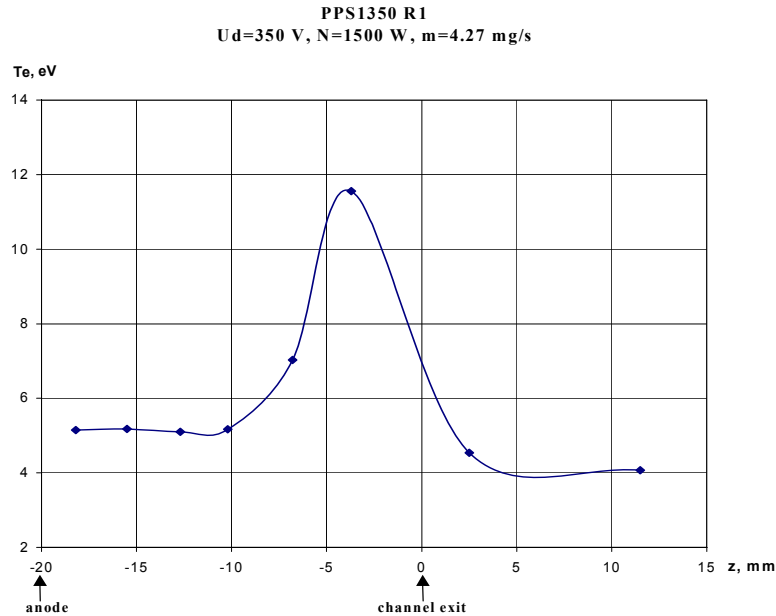


Figure 7. Electron Temperature Distribution Along the Accelerating Channel.

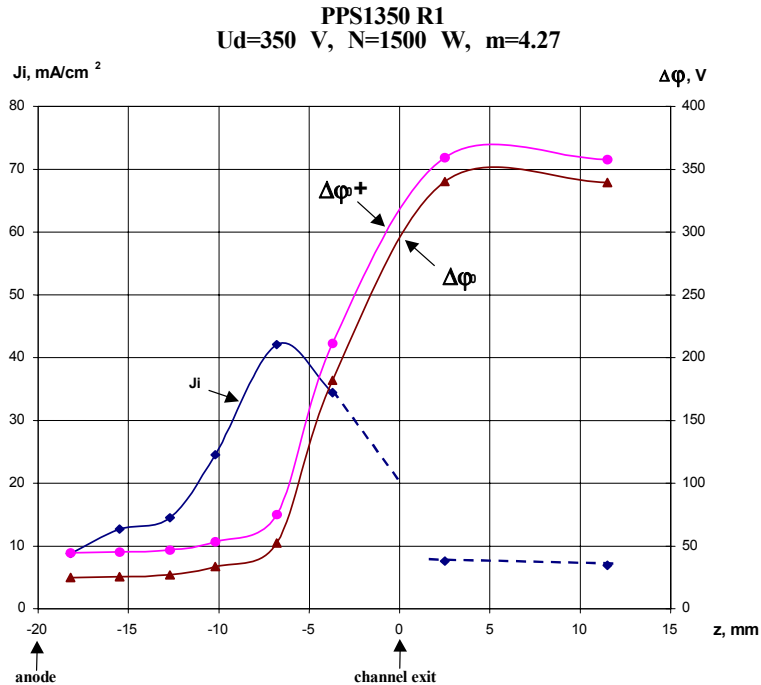


Figure 8. Distributions of the Ion Current and Difference Between Plasma and Floating Potentials.

Multiplying them by ion current density one can obtain the ion kinetic and total power release densities at the wall surface connected with ion and electron flows to the wall. It is necessary to note that reduction of the ion current density along wall near channel exit is to be lower than shown in Fig. 6 because probes installed outside channel were shifted in radial direction and measured reduced current density. Therefore under calculations there were used the extrapolated to the channel exit ion current density values (see dashed lines in Fig. 8). Such calculations show that energy release density reaches its maximum inside the accelerating channel (Fig. 9) and is reduced at the channel exit due to fast reduction of the ion current density from ionization zone to the exit. It is evident also that main part of energy is delivered to walls by ions.

PPS-1350
Ud=350 V, N=1500 W, m=4.27 mg/s

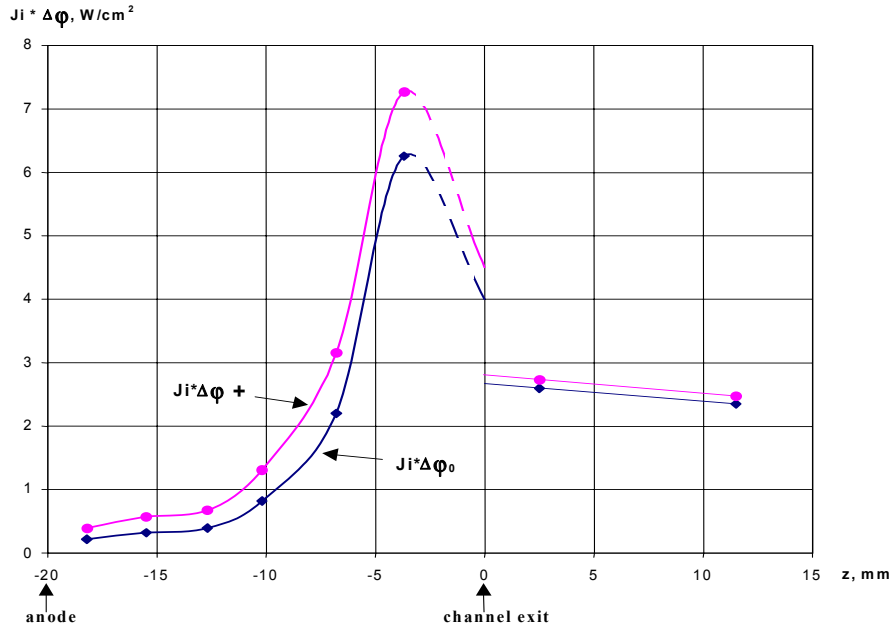


Figure 9. Energy Release Distribution Along the External Wall.

Using these data there was estimated the total possible power release at the exit part of external wall with length ~ 1 cm as $Q \approx 145$ W while estimation of this energy release from the temperature measurements gave value ~ 90 W. If one takes into account that ion energy accommodation factor at ceramics surface is at level of 0.6-0.7 for ions having energy 100-300 eV.³ So, if one takes for estimations the accommodation factor value 0.7, then the power releases determined from thermal measurements and derived from the local plasma parameter measurements are in good agreement. Thus, the methodology for estimation of the power release due to ions impingement with walls with usage of the near wall probes data seems acceptable.

It seems reasonable also to remind that measurement of the plasma potential in the near anode zone allows estimation of the near anode potential drop and of the energy release from plasma to the anode surface. Indeed, the corresponding power P_a can be estimated as

$$P_a \approx I_d \left(\Delta U_a + \frac{3kT_{ea}}{2e} \right), \quad (12)$$

where $I_d, \Delta U_a, kT_{ea}$ are the discharge current, near anode potential drop and temperature, respectively.

Obtained data including the electron temperature measurement results (see Fig. 7) give P_a value under nominal operation mode ~ 53.4 W that is $\sim 3.6\%$ of the discharge power (1500 W). It is necessary to add that accuracy of the probe measurements is not high especially in the part of channel with great gradients of plasma parameter distributions due to impact of oscillations and typically relatively large probe sizes. But in the near anode zone and outside channel probe characteristics are acceptable for standard processing. Therefore, having more or less reliable data in these zones one can get information on the ionization zone and accelerating layer positions at least. Then, it is possible to get reliable enough information on the ion current and probe floating

potential within the whole channel. Taking into account that electrons fraction in the total power release on walls is relatively small the errors in the electron temperature determination lead to reduced errors in the total power release estimations.

The local plasma parameter measurements for the described above laboratory model were made for the operation modes including that ones with increased discharge voltages and mass flow rates.

Table 2. Operation Modes Parameters

Mode	\dot{m}_a , mg/s	U_d , V	I_d , A	T_e , μ N	N , W	C_e , W/ μ N	I_{sp} , s	η_t	$\beta_{0.95}^0$	$Im1$, A	$Im2$, A	$Um1$, B	$Um2$, B	$Im3$, A	$Um3$, B	P_c , Torr
1	N = 1500 W (1)															
	4.27	350	4.28	84.0	1495	17.8	2006	0.553	44.35	1.96	1.42	8.25	2.57	0	400 400	1.4×10^{-4}
2	N = 1500 W (2)															
	4.27	350	4.27	84.3	1497	17.8	2012	0.556	44.25	1.93	1.45	8.16	2.61	0	400 400	1.4×10^{-4}
3	N = 2200 W															
	4.28	501	4.41	104.4	2211	21.2	2490	0.577	47.52	2.28	1.71	10.7	3.29	0	520 490	1.4×10^{-4}
4	N = 3000 W															
	4.27	670	4.54	123	3039	24.6	2944	0.586	45.35	2.21	2.15	10.787	4.32	0	600 570	1.4×10^{-4}
5	N = 3000 W															
	5.51	501	6.00	140	3007	21.5	2591	0.592	43.5	3.00	2.26	15.847	4.61	0	575 550	1.8×10^{-4}
6	N = 2800 W															
	7.24	352	8.00	155	2817	18.1	2187	0.591	43.45	2.39	1.8	11.6	3.652	0	520 500	2.3×10^{-4}
7	N = 3000 W															
	4.6	601	5.00	126	3006	23.8	2799	0.577	51.65	2.58	2.05	13.02	4.19	0	595	1.6×10^{-4}

All obtained results of measurement are qualitatively similar to that ones for the nominal operation mode but there are some specific points to be discussed in more details. First point is related to the magnetic field topology influence, which is notable. So, to separate influence of the magnetic field topology and pure variation of the discharge voltage and mass flow rate there was made an attempt to operate thruster under different discharge voltages with the same ratio of the magnetization currents as for nominal operation mode using only main magnetization coils. It was possible to get operation modes (modes 2, 3, 5, 6 in the Table 2) with close to nominal ratio of magnetization currents and discharge current values close to optimum ones according to discharge current minimum criterion.

Considering obtained data as a whole one can conclude that:

- Increase of the discharge voltage has less impact on the accelerating layer position than an increase of the mass flow rate through the accelerating channel able to cause significant shift of the accelerating layer into anode direction (Fig. 10);
- The ion current distributions are more sensitive to increase of the mass flow rate under low discharge voltage (see case ~ 350 V in Fig. 11);
- Increase of discharge voltage and of the mass flow rate causes an increase of the electron temperature level (Fig. 12).

Impact of the discharge voltage increase can be clarified by consideration of measurement results under fixed mass flow rate (see data for operation modes 2, 3, 4 in the Table 2, Fig. 10...12). These results show that increase of the discharge voltage causes necessity to change the optimum ratio of the magnetization currents (magnetic field topology) at least under ~ 700 V but has no significant impact on the plasma potential distribution. It changes also the electron temperature and ion current distributions increasing their level especially in the near anode zone.

It is to be noted also that typically plasma potential values in the near anode zone relative to cathode potential are close to applied discharge voltage values.

Using obtained data it is possible to estimate variation of the ions kinetic power at external wall with increase of discharge voltage (Fig. 13). Consideration of the obtained data shows that distribution of this power is similar for the chosen operation modes but level of this power is increased more significantly (approximately by two times with increase of discharge voltage from 350 V till 500 V) than increase of discharge voltage or discharge power.

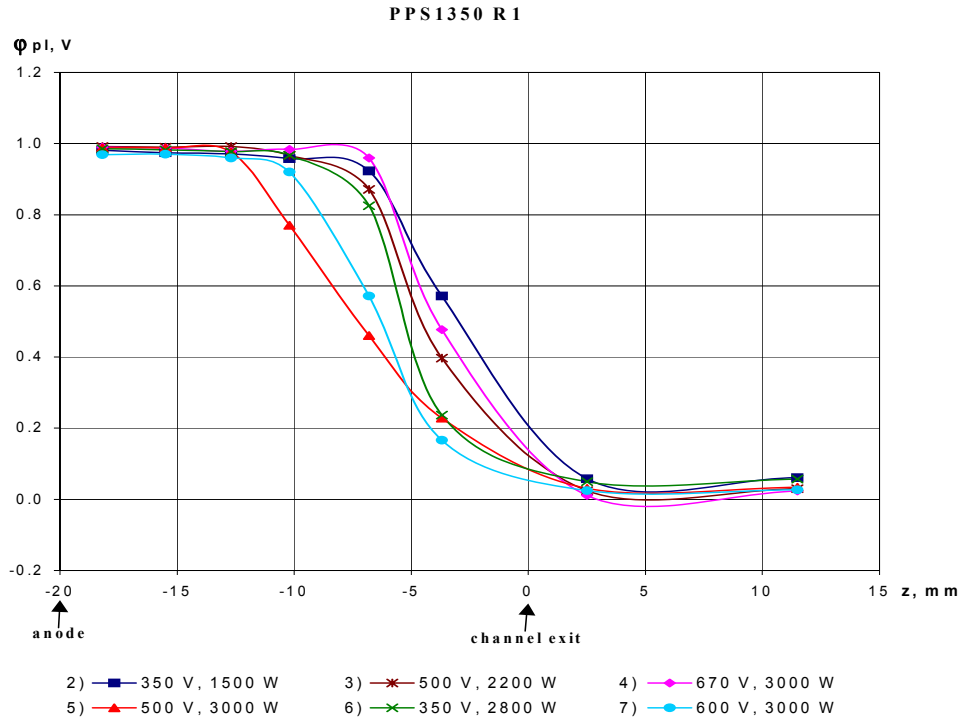


Figure 10. Relative (Divided by Discharge Voltage) Plasma Potential Distributions Under Different Operation Modes.

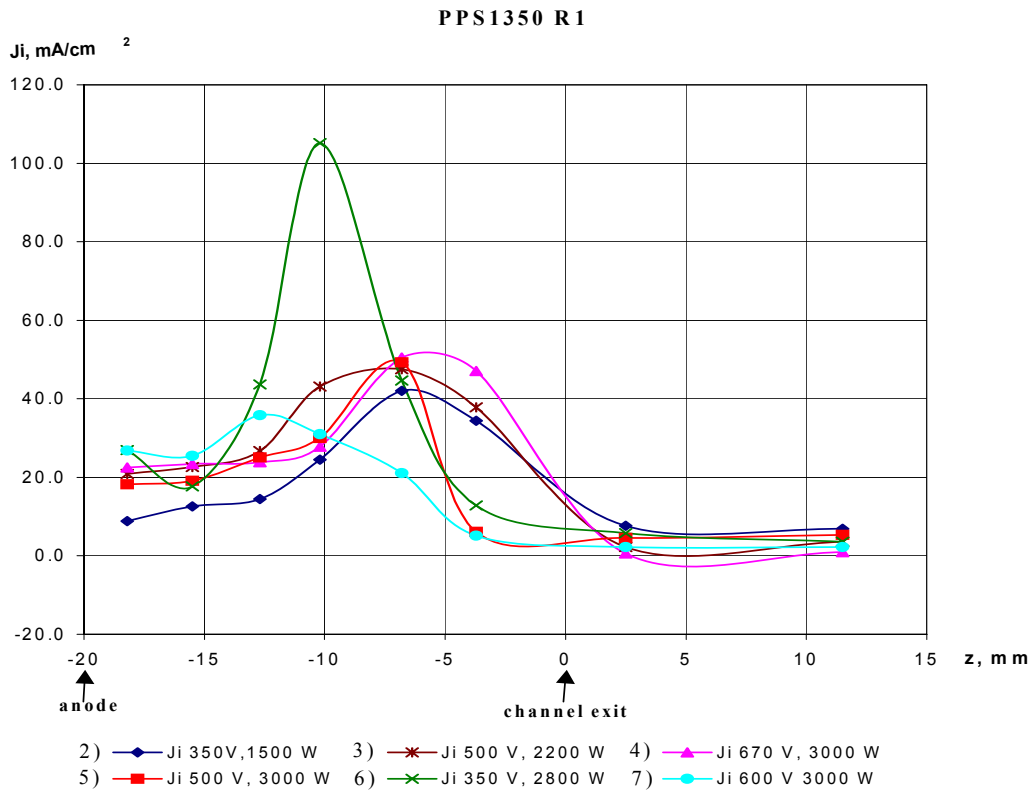


Figure 11. Ion Current Distributions Under Different Operation Modes.

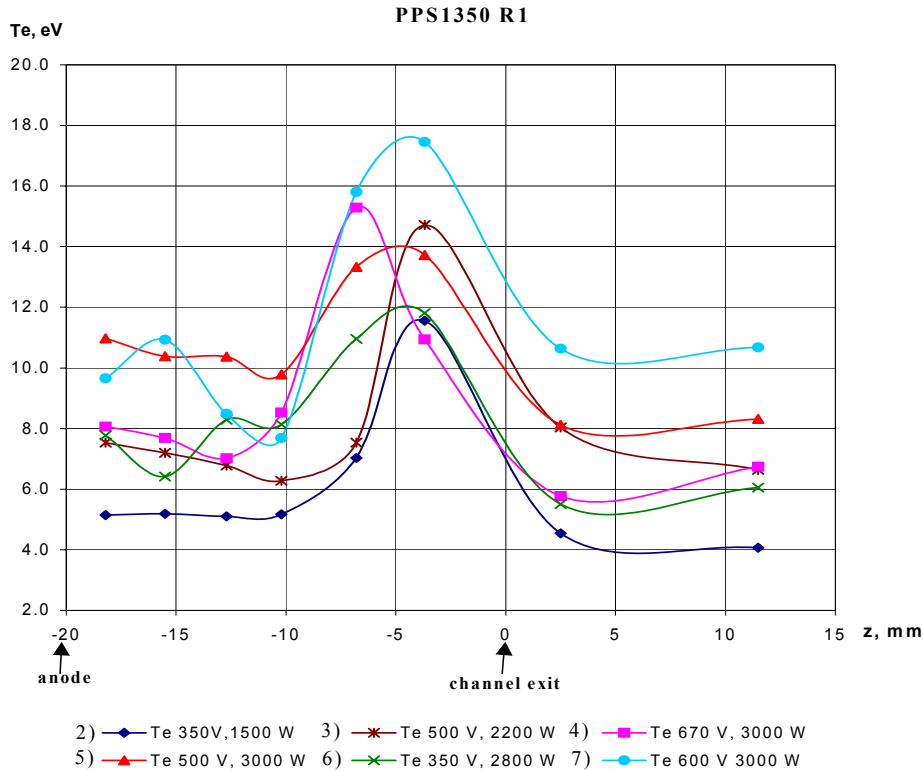


Figure 12. Electron Temperature Distributions Under Different Operation Modes.

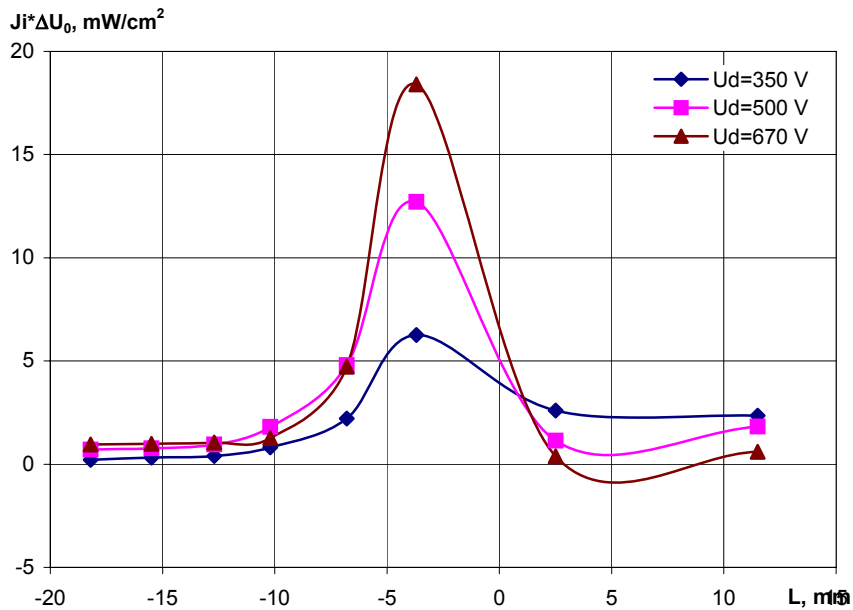


Figure 13. Ions Kinetic Power Density Distribution at External Wall Under Different Discharge Voltages.

This means that one can expect more significant increase of the wall erosion rate due to ions bombardment of walls with increase of discharge voltage under fixed mass flow rate through the accelerating channel. To check this important point there was made the erosion test of the PPS-1350 model during 200 hours. Results of this test had shown that under nominal mass flow rate with increase of discharge voltage from 350 V till 500 V the erosion rate at the beginning of thruster operation is increased approximately by two times (Fig. 14) in correspondence with data indicated in Fig. 13.

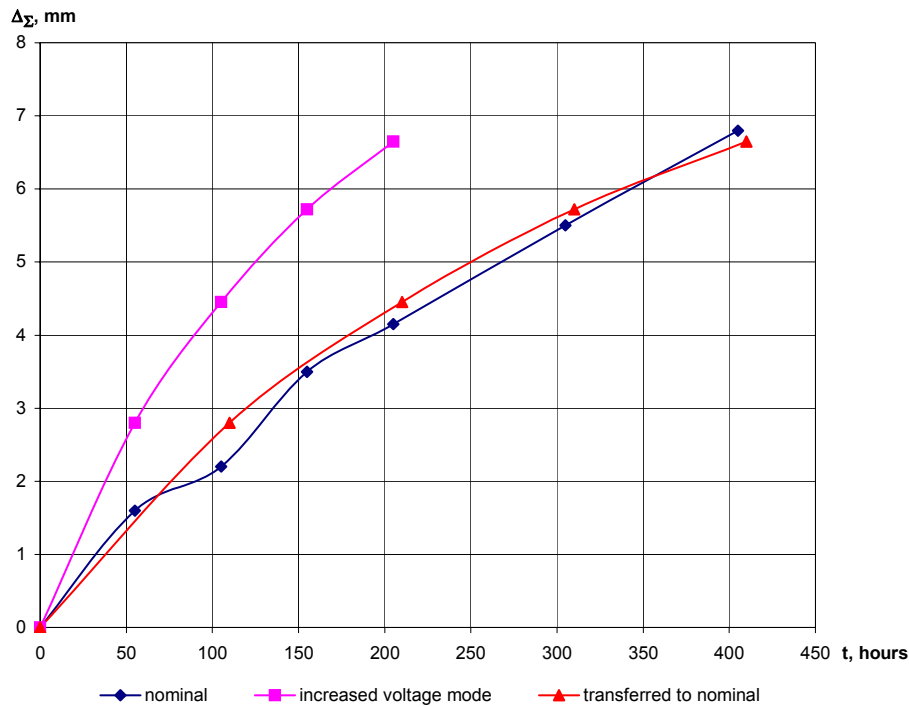


Figure 14. Dependence of Total Erosion Rate on Time

Results, similar to presented above, allow estimation of the total ion current losses I_{iw} on the discharge chamber walls. For example, under nominal operation mode the total ion current to external wall was ~ 1.4 A, that is ~ 45 % of current $I_m = \frac{\dot{m}_a}{M} e$, equivalent to the mass flow rate \dot{m}_a through the accelerating channel. This result is in correspondence with earlier data and means that after neutralization of ions on walls the appeared atoms are ionized again because the total current of ions leaving thruster is close to I_m .

As a whole obtained data confirm usefulness of the described approach to the local plasma parameter measurements and necessity to improve methodology of measurements. Particularly it is necessary to improve methodology of the wall temperature measurements what is not so simple in the ceramic wall case.

IV. Conclusion

The local plasma parameter distribution measurements were made along external SPT discharge chamber wall and it was shown that such measurements allow to estimate ions and power losses at the mentioned wall as well as to estimate influence of design and operation mode parameters on position of the ionization zone and of the accelerating layer relative to the accelerating channel. It is shown that power release on the walls due to ions impingement with them is at level of (15-20)% of discharge power for modern SPT's. Therefore such measurements will be continued and methodology of measurements is to be improved to ensure better their accuracy.

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