Some results of the small power SPT models creation

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Abstract

The analysis of the space technology development shows that the share of small weight space crafts for the telecommunication and monitoring tasks are increased steadily. The peculiarity of these spacecrafts is the limitation for the electric power (100-300 W), which is possible to give for thrust operation. Nowadays at the active operation time up to five years the existing models of the electrorocket thrusters (ERT) can't be competitive with traditional thrust systems. The ERT break to the small satellites is possible if the high efficiency thrusters' models with power less than 300 W will be created. On its base the multy-modes power plants, which can solve different problems, such as satellites constellation delivering to the phase points and then maintaining of the space craft location in the phase space, can be originated. MAI department "Spacecraft Electric Propulsion and Powerplants" experience in this field of science permits to look at such ERT creation with optimism. MAI scientific experience concerning small power stationary plasma thrusters (SPT) development is represented in this report. The last results concerning the investigations of the thrusters with power 200-400W are represented too.

1. Main results about small SPT performance investigation

The works with the small power thrusters have been started MAI 15 years ago. The aims of these investigations are to clarify the main regularities, determining the output performances and to create the models-prototypes of the high efficiency thrusters for prescribed power level. During the whole test program emphasise to the investigations of the models operation in the wide range of the performances was done.

As the result of carried out investigation the main regularities of the magnetic field distribution in the acceleration channel and its influence, simultaneously with the discharge chamber geometry, to the performances of the examined models. The empirical dependencies, permitting to forecast the thruster parameters under its designing are obtained.

All SPT's existed models, which flew many times in space, operated under power of more than 400 W. But for the small satellite the power consumption should be significantly lower. Therefore it was interesting to analyze if it is possible to create effective enough thrusters operating under power lower than 300 W. There is a problem of ensuring high enough level of the thrust efficiency for such thrusters, namely: in order to receive sufficient ionization efficiency in the accelerating channel of SPT's it's necessary to fulfill general condition[1]:

$$\lambda_i \le \delta_c , \qquad (1)$$

where $\lambda_i \approx \dfrac{v_a}{<\sigma_i v_e> n_e}$ - free path of atoms before their ionization; $<\sigma_i v_e>$ - ionization rate factor depending on the electron temperature T_e and gas properties; v_e - electron velocity; n_e - electron density of plasma in the accelerating channel; v_a - atom velocity; δ_c - the acceleration channel length.

For the traditional SPT accelerating channel geometry the relationship (1) could be transform to the following one[1]:

$$\frac{\dot{m}}{Md} \ge k_1 \frac{v_a v_i}{<\sigma_i v_e>} U_d d , \qquad (2)$$

where $\dot{m}$ - mass flow rate, k_1 - const, d - characteristic diameter of the accelerating channel; $v_i \approx k_2 \sqrt{\dfrac{U_d}{M}}$ - mean value of ion velocities in the accelerating channel; U_d and M - the discharge voltage and ion mass correspondingly, k_2 - const.

Taking into account that discharge current I_d in the SPT is in a first approximation proportional to the mass flow rate we can show that the discharge power can be estimated as:

$$N_d = U_d I_d \approx k_s \frac{v_a v_i}{<\sigma_i v_e>} U_d d. \qquad (3)$$

The level of discharge voltage is determined the ion velocity, T_e and $<\sigma_i v_e>$ value levels. Therefore it's difficult to reduce U_d lower than (120-150)V. That means that in order to reduce significantly the power and still maintain a high ionization efficiency it is necessary to decrease d, or the sizes of the thruster. The thruster size decrease is limited by the necessity to obtain the optimal value of magnetic field induction and its topology. Another opportunity of course is to allow the decrease of ionization and thrust efficiency with decreasing of discharge power level and thruster size. In the fig.1 the optimal parameters arias for the thrusters with power 300 and 100 W, obtained as the calculation results and verified experimentally are represented. It is important to assess what level of efficiencies could be received for the small SPT. Such a task is multyparametric. Therefore an experimental investigation was made and general results of this investigation will be presented below.

For the performance estimation some models of small SPT were designed. Their accelerating channel external diameters d are 32, 40 and 50 mm. In general their integral parameters variation, obtained in the experiments have the same character as for the standard SPT. The general results (fig. 2) permit us to conclude, that one can see a tendency of decreasing in thrust efficiency with the lowering of the model diameter. This tendency obviously leads to the accelerating channel size decrease limitation. Nevertheless for the models with d=40 ...50 mm the effectiveness is still acceptable. The main reason of this is that it's impossible for the magnet systems of small size SPT to create the optimum intensity and configuration of the magnetic field in the accelerating channel. Analysis of the experimental data shows that it is possible to create the optimal topology in the C-type magnetic systems only if as minimum two sources of the magnetic-motion forces of high efficiency are used. It is especially important for the part of the magnetic circuit of the small size thruster, located inside the acceleration channel. So, taking into account the thickness of the ceramic wall, which is necessary for the acceptable lifetime, there is practically no place to locate the correcting source of the magnetic-motion force. The analysis shows that if we use the electromagnets for the field creation, the minimum middle diameter of the channel can not be less than 18-20 mm, in this case the optimal width of the channel is in the limits $d/6<\delta_c<d/4$. This problem can be partially solved if one will use permanent magnets for correction of magnetic field topology in the accelerating channel. This solution was tested in all examined models of SPT and demonstrated satisfactory performances. Evidently, that without special cooling system, permanent magnets can be used for the field topology correction only under the model's power less than 100 W. But even for the low power models the permanent magnets is not very good solution, because in this case it is possible to create only the single-mode operation thruster in order to provide the magnets long time work.

Analyzing ourselves results and the results published in the recent time[2,3] it was found out that if it is necessary to create the model with power less than 50-70 W, it is reasonable to pass from SPT scheme to the thruster with the anode layer without ceramic elements in the discharge chamber structure, which is used in order to form the main discharge zone. But in this case it is necessary to carry out an additional investigation in order to solve the life time problem.

The last results was implemented in the model SPT-50 developed in our department. Its optimized magnetic systems permitted to obtain slightly higher performances relatively the traditional level (points, marked by * in the fig.2). These results were verified during test in NASA LRC Cleveland[2]. Unfortunately the authors of the mentioned report[2] incorrectly point the organization, in which this SPT-50 thruster model was created.

2. Analysis of performance increasing possibility for low thrust SPT

Moreover our understanding of physical processes and developed structural schemes of the SPT does not permit us to solve the problem how to create the perspective power plant of small power with significantly high operational and thrust performances. The analysis of thrust efficiency main losses in the SPT showed that mainly they are (without cathode looses):

- ripple-through carry electron current - up to 25%;
- discharge power onto ion beam divergence - up to 10%;
- losses due to ions average energy is not corresponded to total accelerating potential - up to 10%[1].

Let's examine how we can increase SPT efficiency. The main part of the channel length is occupied by so-called near anode zone. In this zone there is potential maximum and $E_z \leq 0$ and we don't know exactly this zone role in the organization of the operation processes. Small value of the longitudinal electric field

E_z under great radial one mainly determine big divergence of ion flux and ions losses on the channel walls. That's why resulted ions cost is increased and energetic efficiency of the thruster is decreased. In our previous work[4] it was mentioned that it is possible to decrease the resulted ion cost and corresponding losses decrease by the account of channel initial length reduction.

Lets analyze what will happen if we realize this idea. Processes, forming the electric field and discharge current fall onto anode by electrons are the main important. As far as electric field in the near anode zone is determined mainly by electrons pressure gradient ∇p_e[5], then under near anode zone reduction the intensity of the longitudinal electric field module $|E_z|$ will be increased, plasma potential will be increased and negative influence of radial component will decrease. Anode approach to the boundary of the ionization and acceleration zone must "simplify" the conditions of electron current fall onto anode. In this case it is possible to assume, that the share of energy, bringing by electrons from acceleration and ionization layer and going onto support of negative near anode potential drop, will be increased. As a result of it is possible to expect that ion average energy in the plume will be increased and acceleration efficiency will be increased.

The preliminary[4] results permit us to do the following conclusions:

- SPT can stable operate if the acceleration channel length is decreased up to value equal to channel width $L_c=\delta_c$ without spoiling the thrust performances. In this case the value of the magnetic field induction near anode can be $\sim 0.3\ B_{r,max}$;
- in order to reach significantly great level of the thrust performances and stable operational mode of the SPT with short acceleration channel, it is necessary to secure high azimuth uniformity of propellant feeding and accuracy of anode setting.

The results totality, obtained under investigation of accelerators' models with short channel[4], permits to clarify the main peculiarities of their operational processes. It is possible to analyze qualitatively mechanism of anode location action onto plasma inside acceleration channel, comparing local parameters distribution[4], obtained for traditional and new schemes. Its analysis can explain why in the model with sort channel there was not able to increase thrust efficiency inspite of initial length reduction. It is mainly depends on electrons temperature increasing and increasing of ion current density on walls in the near anode area that is determined non-effective energy cost on channel length unit.

Let's examine how results of local measurements[4] correspond to modern theoretical concepts. Variating magnetic field $B_r(z)$ and electron pressure gradient ∇p_e distributions over channel length, one can control self-coordinating electric field formation. It is clear from the dependence for axis component of electric field intensity vector, obtained from Ohm law in the frames of non-collision model for two-component ideal plasma:

$$E_z=\frac{J_\varphi B_r}{en_e}-\frac{\nabla p_e}{en_e}, \tag{4}$$

where B_r - radial component of magnetic field induction; p_e – electron's pressure; J_φ - density of the electron azimuth current; n_e - electrons concentration.

In the work[4] we showed experimentally that it is possible to control the electron pressure gradient and correspondingly of the electric field distribution, variating the characteristic size of the near anode zone $L_{na} \sim \Delta z$. Further analysis shows that it is better to control of ∇p_e changing directly the electron pressure difference Δp_e over channel length. So, decreasing p_e near anode and by this way increasing electron pressure gradient ∇p_e, it is possible to control the electric field distribution E_z over channel length.

Channel walls play very important role during electric field in the near anode zone formation. In the fig.3 the magnetic force lines configuration in the SPT channel, obtained by analogy simulation on electrolytic bath, is represented. One can see that in near anode zone, magnetic force lines have great curvature. Because of it the mechanism of electrons transition onto channel walls must be the same, as on anode, in particular, across magnetic field. For every point of de-electrical wall the condition of ion and electron currents equality must be fulfilled. In this case the dependence for discharge current density[6]:

$$j_d=eD_\perp \nabla n_e+e\mu_\perp n_e E_z, \tag{5}$$

where $D_\perp$ and $\mu_\perp$ - diffusion coefficient and coefficient of electron mobility across magnetic field can be written as:

$$eD_\perp \nabla n_{e,wall}+e\mu_\perp n_e E_{wall}=j_{i,wall}, \tag{6}$$

where j_{iwall} - ion current density onto wall.

Channel wall influences onto electric field formation. In this case $E_{wall} < 0$ module is decreased in the direction of wall and in the focusing structure of the electric field in the near anode zone, which is qualitatively represented in fig.4. As far as $j_{iwall} << j_d$ then as it follows from (6), channel wall influence onto electric field formation is greater than anode influence. If we increase channel width in the near anode zone - δ_{na} , electrons concentration gradient in the direction of wall dn_{wall}/dr is decreased because characteristic size $\delta_{na} \sim \Delta r$ is increased. This in its term, according to (6) must decrease electric field intensity E_{wall} in the direction of channel wall and improve ion flux focusing.

Propellant atoms ionization intensity in the nearanode zone is decreased because of concentration of neutral and charged particles is decreased and also density of the heat fluxes onto structure elements are decreased and it should decreased the resulted ion cost and increased SPT energetic efficiency - all these are the advantages of the suggested solution.

At the end of analysis it is necessary to decide where the expansion of the near anode part of the channel must begin. In the standard SPT models the boundary of the acceleration zone in the near anode zone of the discharge with $E_z \sim 0$ usually located in the area of 8...12 mm from the channel cut. As far as the expansion of the near anode part should lead to the main potential drop layer restriction, it is reasonable to locate the expansion nearer to the channel cut. So, if one is designing the model of the acceleration with modified near anode zone, we can recommend that expansion will coincide with the boundary of the channel wall erosion zone.

3. Experimental model development and test

Basing on the standard model of the SPT – 50 [2], the model of the thruster with expanded near anode part was developed. Location of the expansion boundary of the near anode part of the channel corresponds to the width of the wall erosion zone in the standard model, the shoulder's depth on the both walls is about some mm. The expansion of the near anode part is reasonable to do on both (external and internal) walls of the acceleration channel. Besides, the shoulder on internal and external walls of the channel is reasonable to locate in one (normal to the accelerator's axis) plate. It permits to overcome the additional misalignment of accelerating layer over internal and external walls when near anode part of the discharge chamber is expanded.

SPT-50 modified model test in the discharge potential range U_d=120...320 V and flow rate $\dot{m}_a$ =1...2 mg/s showed that it is possible to increase the thrust characteristics for models with small power if near anode part of the channel is expanded. Comparison between base and modified models shows that thrust efficiency is increased on 7...10% (fig.5) and it is connected with thrust increase. Ion beam parameters measurement confirms that thrust increase is connected with the improvement of ions focusing (fig.6). Ion beam divergence is decreased on 20% relatively SPT-50.

One of the main important results is the fact, that accelerator's main parameters are increased under discharge small power. In the fig.7 the performance comparison under discharge power N=300 W are represented. One can see that in modified model it was able to increase the main parameters and to reach modern level of the performances for SPT of great power and sizes [7].

Conclusions

So, the results of SPT - 50 model comparative tests permit to make the following conclusions:

- expansion of near anode part of the channel permits to improve SPT thrust characteristics on 7...10% and to decrease the ion beam divergence half angle on 5...10^0;
- it is possible to create SPT with small power with increased performances up to the level of the traditional models.

The scientific works concerning of small power thrusters in MAI are continuing.

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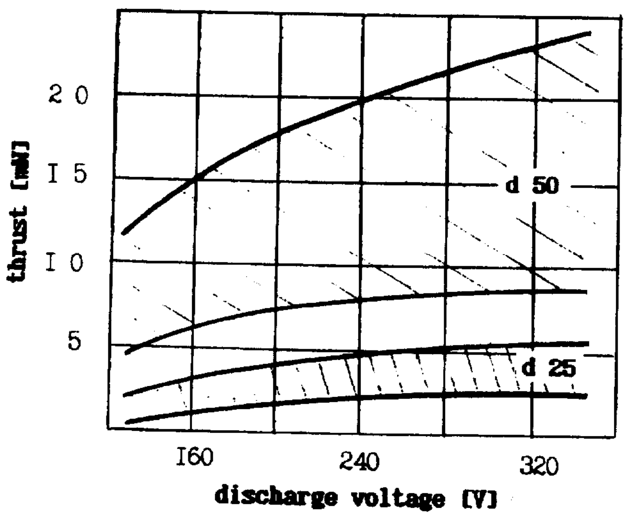

Fig.1

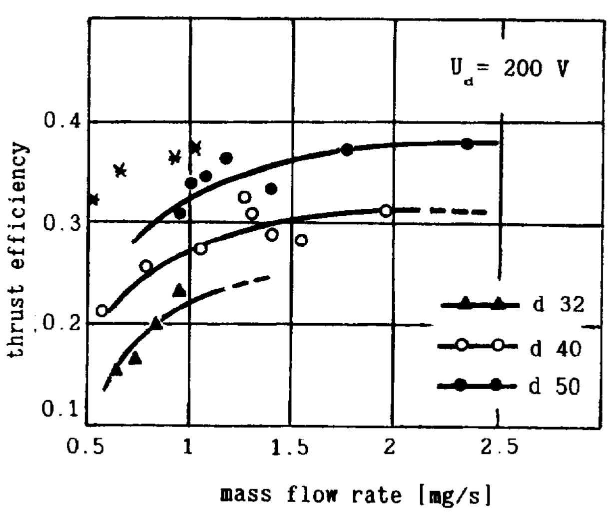

Fig.2

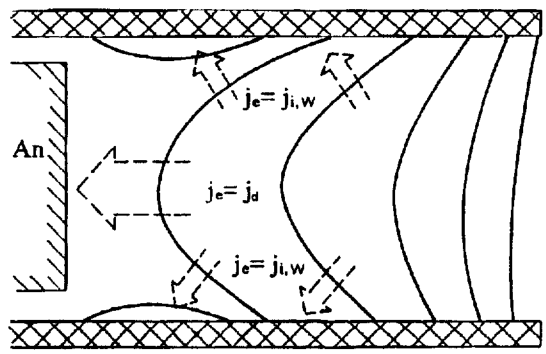

Fig.3

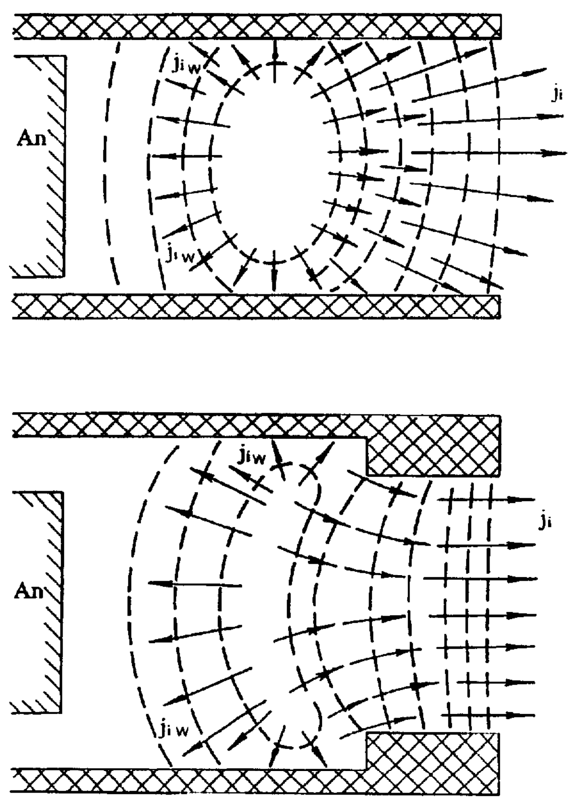

Fig.4

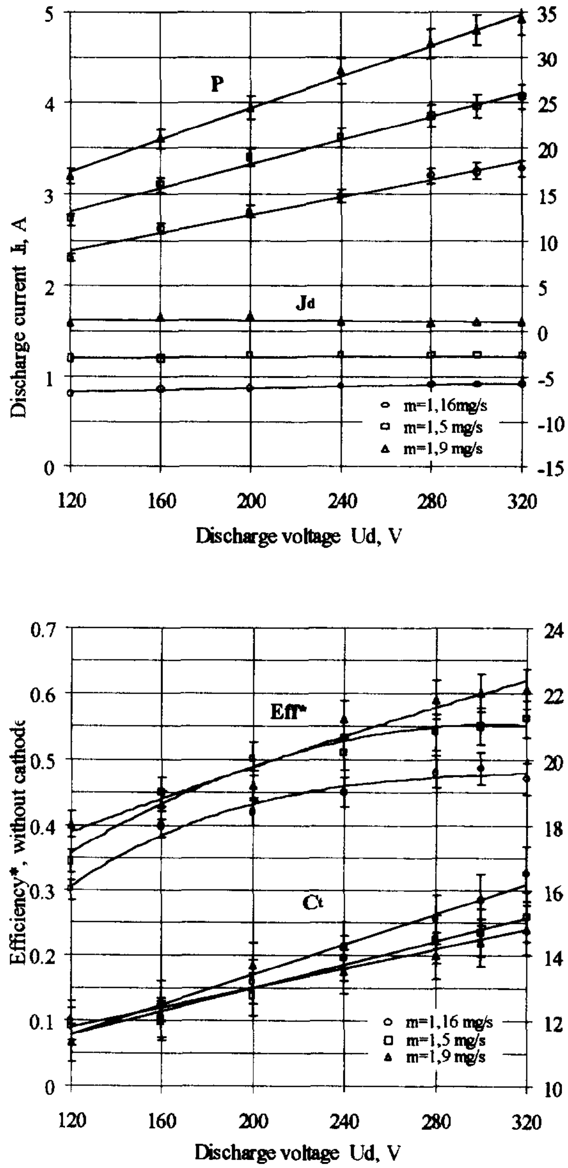

Fig.5

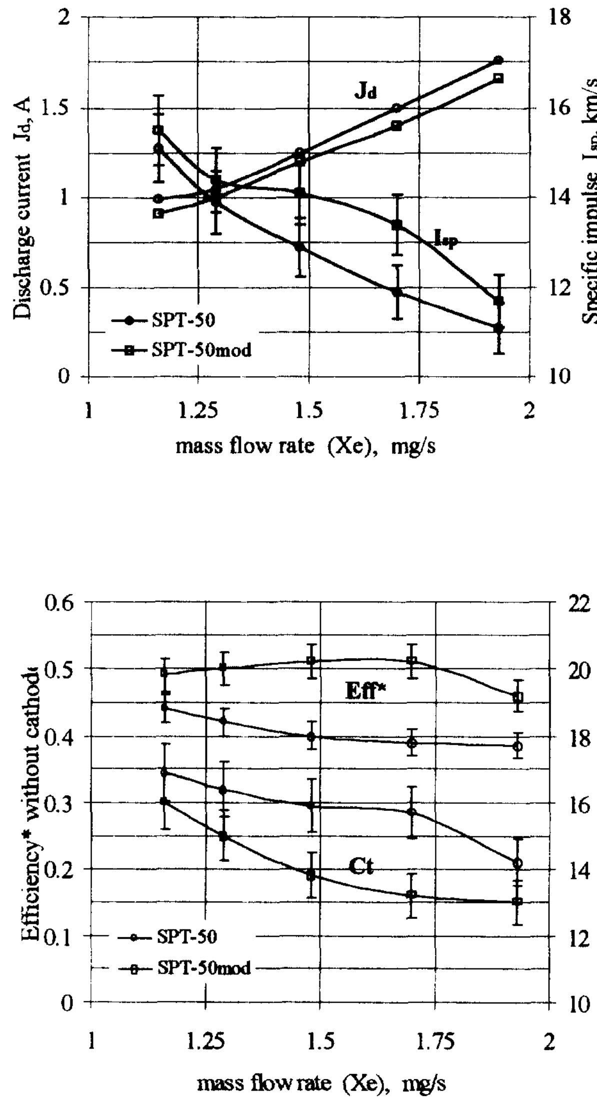

Fig.7

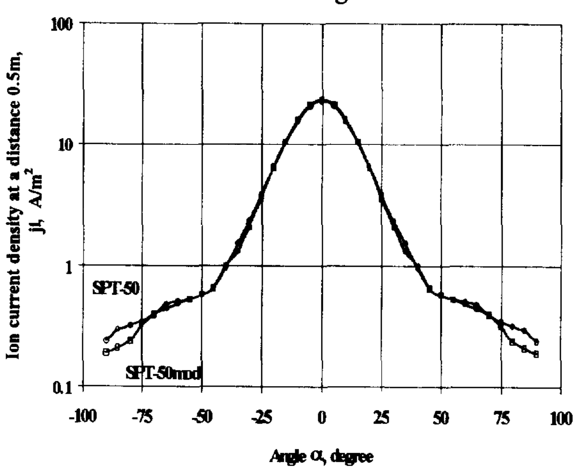

Fig.6