Investigation of the possibility to develop a competitive low power Stationary Plasma Thruster

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Abstract: **Results of a low power Stationary Plasma Thruster (SPT) development are represented in the paper. It is known that this is a difficult problem due to the necessity to reduce thruster sizes to ensure the SPT satisfactory operation. Due to reduction of thruster sizes it is difficult also to get large thruster lifetime. Especially it is difficult for the low power SPT operating with Krypton. The different approaches to solve this problem are known and that one used during the upgraded SPT-100PM and SPT-140PM model development was used in this study. According to the mentioned approach the ionization and acceleration layer is shifted in the exit direction relative to the thruster design by increase of the magnetic induction gradient in the longitudinal direction and by shifting the magnetic yцinduction distribution maximum along the mentioned direction outside the minimal surface surrounding the magnetic system elements. Additionally there was used a widening of the accelerating channel exit part to reduce ion flows to the discharge chamber walls and corresponding energy release on walls as well as to reduce influence of the plasma–wall interaction on IAL thickness. Combination of these solutions allows positioning of the IAL and of the wall erosion zones outside the mentioned minimal surface. Performance determination and erosion tests of the SPT-40M model with the external accelerating channel around 40mm had confirmed the possibility to position IAL and the wall erosion zones fully out of the magnetic pole plane while this model was operating with Xenon and Krypton with the discharge powers 200W and 250W, respectively. Such positioning of IAL and erosion zones outside the mentioned minimal surface allows creation of the increased**

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thicknesses of walls protecting the magnetic poles and ensuring the possibility to obtain increased low power SPT life time.

Nomenclature

b_{ch}	=	acceleration channel width
I_m	=	propellant flow current
$\dot{m}_a$	=	propellant mass flow rate through the acceleration channel
e	=	electron charge
M	=	propellant atom mass
n_e	=	electron concentration
λ_i	=	free path of the propellant atoms before ionization
V_a	=	atoms velocity
$\langle \sigma_i V_e \rangle$	=	ionization rate factor
L	=	longitudinal size (thickness) of the ionization and acceleration layer

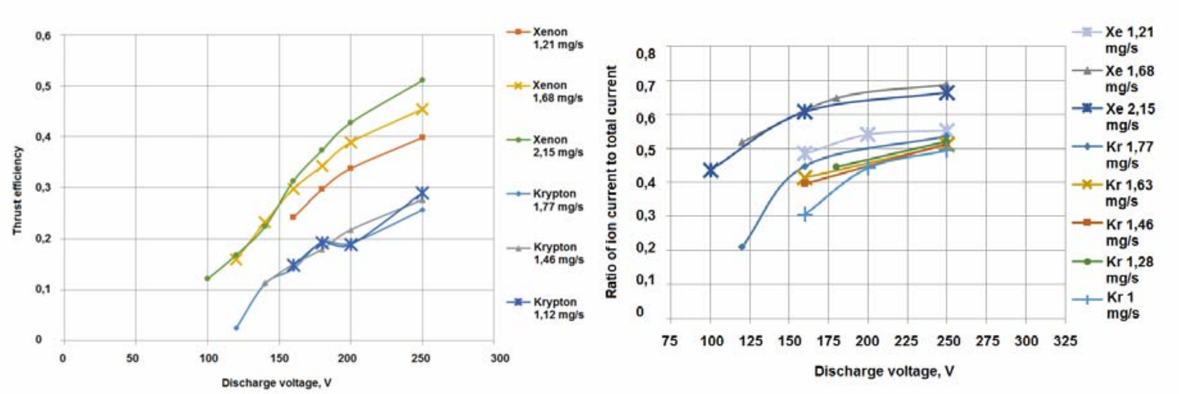
I. Introduction

As it is well known the Stationary Plasma Thrusters (SPT) operating with xenon are successfully used in the systems of the spacecraft motion control already many years [1]. The simplicity of the SPT principal scheme and design ensures the possibility to create relatively simple and reliable propulsion systems (PS) on their base. In combination with the high enough thrust efficiency with moderate specific impulses the mentioned simplicity explains the fact that SPT had become the mostly often used electric propulsion thruster (EPT) in the near Earth space [1]. In connection with increase of the small satellites (minisats) application for the Earth observation and communication especially by creation of the constellations consisting of the large number of minisats it is reasonable to use the low power EPT's for their orbit control. Therefore many low power EPT's of different types are nowadays under development [2]. For low power SPT to be competitive it is necessary to improve its thrust efficiency and to ensure large life time. It's interesting also to replace xenon by cheaper alternative propellant. One of them is Krypton which is more than an order of magnitude cheaper than xenon and also do not cause the spacecraft contamination by the exhausting thruster propellant flows. And nowadays one of SPT's operates with Krypton in the Starlink constellation [3]. According to the preliminary estimations its power is probably around 500W or higher. In some other missions the thrusters with powers less than 500W could be used also. Taking this into account the main goal of the given study was investigation of the possibility to develop the KrSPT satisfactory operating with power not exceeding 250W. And results of this study are represented below. Some data were obtained also while the developed SPT model was operating with Xenon.

II. Results of investigations

A. Problems and approach to the low power SPT development

As it is known the development of the low power SPT with satisfactory efficiency and large life time is a difficult task even for SPT operating with Xenon (XeSPT) due to the necessity the difficulties of the magnetic field optimization in the SPT discharge because the optimum magnetic induction is increased with the reduction of the acceleration channel width b_{ch} approximately proportionally to $1/b_{ch}$. But this increase of induction is limited due to reduction of the magnetic core elements. Then, it is more difficult to ensure the large life time of the low power SPT because with the fixed discharge power density and reduction of thruster sizes the discharge chamber wall thicknesses and life time are reduced in the first approximation proportionally to b_{ch}. At the same time requirements to the low power SPT life time are comparable with that ones of the medium power thrusters. Thus, the problem of the large life time obtaining for the low power SPT becomes critical, especially for thrusters operating with Krypton. Indeed, many studies of the SPT operation with Krypton (KrSPT) and their performance show that for the typical SPT operation modes the KrSPT thrust efficiency is lower than that one of the XeSPT [5-10] and this difference for the low power SPT can reach 20% (Figure 1a, [11]). One of the main reasons of the mentioned difference is the lower mass utilization efficiency of Krypton what is confirmed by the lower ratio of the ion current *Ji* in the exhausting KrSPT flow to the total “propellant flow current” $I_m = \dot{m}_a e / M$ through thruster (Figure 1b, [11]), $\dot{m}_a, e, M$ where are the propellant mass flow rate through the acceleration channel, electron charge and propellant atom mass, respectively).



a) **b)**

Figure 1- Dependence of the SPT-50 thrust efficiency and ratio of ion current to total current on the operation mode

It was found also that the main factor allowing increase of the KrSPT thrust efficiency is an increase of the mass flow rate through the acceleration channel. This is understandable because increase of the mass flow rate causes an increase of the plasma (electron) concentration n_e in the ionization and acceleration layer (IAL, where the main potential drop is occurred) due to reduction of λ_i / L ratio, where $\lambda_i = V_a / \langle \sigma_i V_e \rangle n_e$ is the free path of the propellant atoms before their ionization, $V_a, \langle \sigma_i V_e \rangle$ are the atoms velocity and ionization rate factor and L is the longitudinal size (thickness) of IAL. More over it was found that the same level of the SPT-140PM model thrust efficiency maximum as that one of the XeSPT could be obtained with the sufficient mass flow rate through the acceleration channel (Figure 2, [12]). It was found also that the mentioned maximum of the thrust efficiency is achieved approximately with the same mass flow rate density in the acceleration channel ~0,1 $mg / s \cdot cm^2$ for the KrSPT and XeSPT, if it is calculated using the acceleration channel exit cross-section area taking into account its widening [12]. And this condition complicates the problem of the effective KrSPT development in general because with the same mass flow rate density the discharge current and discharge power are to be larger in the KrSPT due to lower mass of the Krypton atoms. This means that for obtaining of the comparable thrust efficiency with the same discharge voltages the KrSPT is to be operated with larger discharge power. So, KrSPT is to be of smaller sizes than the XeSPT operating with the same power and this is an additional complication of the low power KrSPT development.

Thus, to ensure the acceptable thrust efficiency and large life time of the low power KrSPT it is necessary to use the special measures. And in the given study an attempt was tried to apply the same approach which had given hopeful results in the improved medium power SPT developments. Particularly last years there were developed the modified SPT -100PM [13] and SPT-140PM [12] models at Research Institute of Applied Mechanics and Electrodynamics of Moscow Aviation Institute (RIAME MAI) with IAL shifted in the exit direction more significantly than in the well known serial SPT-100 and SPT -140 thrusters of the same

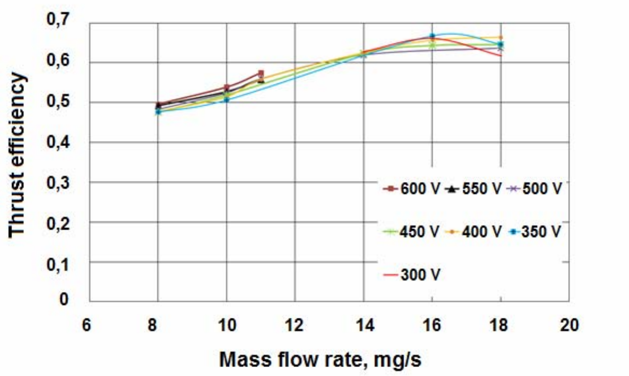


Figure 2 - Dependence of the SPT-140PM thrust efficiency operating with Krypton on the mass flow rate through the acceleration channel (the digits in the legend indicate the values of the discharge voltage).

scales. This was achieved by narrowing and more significant shifting in the exit direction of the magnetic induction distribution maximum than in existing serial thrusters combined with the widening of the acceleration channel exit part to reduce the accelerated ion flows to the walls and corresponding energy release according to ideas presented in [14]. The widening of the channel with angles 45 degrees at each wall was chosen in the mentioned models taking into account that during the SPT-100 life time tests after reaching of widening angles 30-45 degrees at each wall there was stopped the further shift of the erosion zone boundaries toward anode [15]. Thus, it was possible to conclude that under such and greater widening an influence of the plasma - wall interaction on the thickness of IAL becomes small and position of the IAL is stabilized. The mentioned widening and reduction of the ion flows to walls allows operation of thruster with increased mass flow rates and discharge powers and IAL positioning fully in the exit part of the acceleration channel widened beyond the magnetic poles plane. Such position of IAL allows increase of the wall thicknesses and margin for their erosion in the free space beyond the magnetic pole plane increasing thruster life time. The possibility to increase the mass flow rate allows also an obtaining of the high mass utilization efficiency and thrust efficiency even in the thruster with widened channel [12].

Investigation of the modified SPT-100PM model performance operating with Xenon had confirmed an effective its operation with increased at least twice mass flow rates and discharge powers without overheating of its structural elements. Therefore on its base there were developed and tested the SPT -100VT mock-up (SPT-100VT-M) and the SPT-100VT–EM engineering model designated to operate with powers till 3 kW [13]. The 60-hour EM SPT-100VT-M and 80–hour SPT-100VT–EM erosion tests with discharge voltage 300V and discharge power around 3kW had confirmed the stability of their parameters and high level of thrust efficiency and specific impulse (Figure 3). And what is important the wall erosion zones were fully positioned in the widened exit part of channel positioned out of the magnetic pole plane (Figure 4) and the erosion rates were comparable with that ones obtained during SPT-100 life test with the similar wall geometries [15]. Therefore it seems possible to increase margin for the wall erosion and to increase SPT-100VT life time at least till the level of the SPT-100 life time.

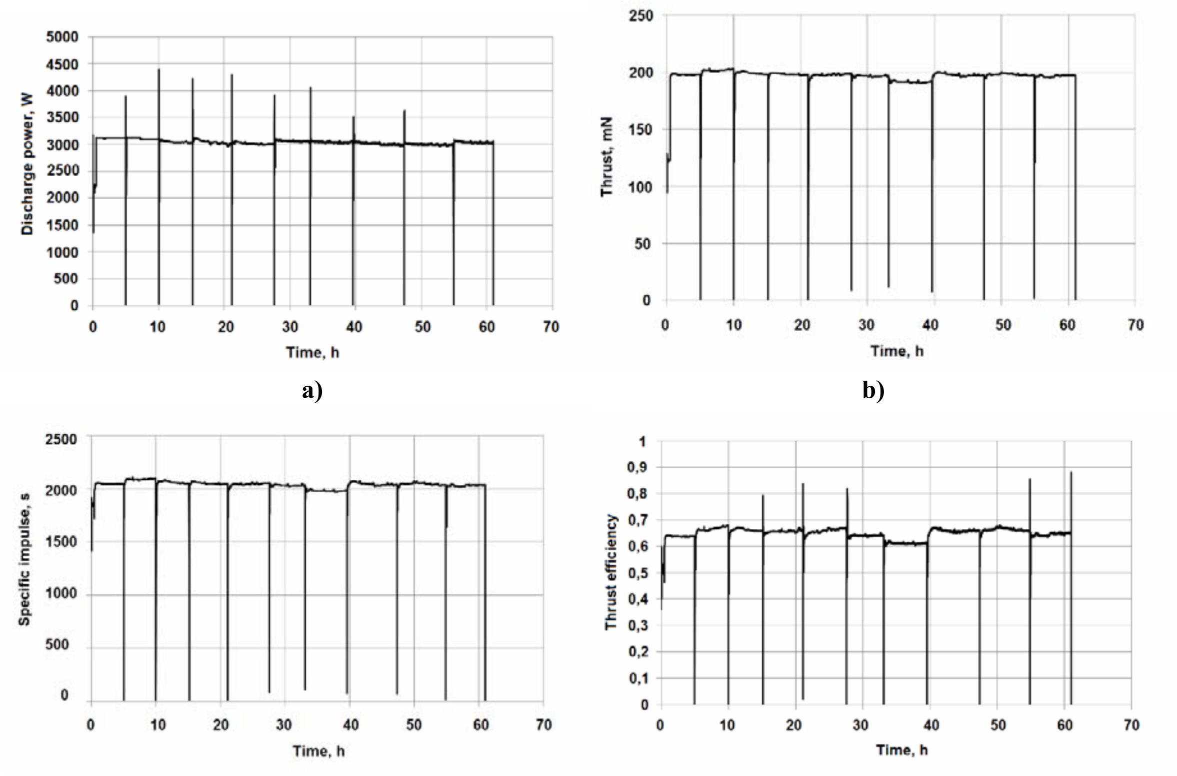


Figure 3 - The SPT-100VT-M parameter variation in time during its erosion test

The SPT-140PM model was also modified using the considered above approach and its performance were investigated with Xenon and Krypton. For the given case more interesting to discuss results obtained with Krypton. Particularly it was obtained that thrust efficiency over 60% could be obtained with the discharge powers over 7 kW [16]. Then, this model also have passed 50-hour erosion test operating with Krypton, discharge voltage 400V and discharge power around 10 kW demonstrating thrust around 500 mN, thrust efficiency over 60% and specific impulse over 2600s (Figure 5) which is at least by 15% higher than that one obtained with Xenon and the same discharge voltage [12,16].

It is important that erosion zones in the SPT140PM model were also fully positioned in the exit parts of acceleration channel widened starting approximately from the magnetic pole plane and wall erosion rates were comparable with the erosion rates of the SPT-100 walls during life test with the comparable channel geometries. Thus, obtained results confirm the feasibility of approach used for the considered models modification. And it was decided to use it for the low power KrSPT experimental model development.

As was noted above in the given study it was assumed that the nominal power of the developed low power KrSPT is to be around 250 W. Therefore taking into account the mentioned boundary mass flow rate density for obtaining of more or less efficient thruster operation an external acceleration channel diameter of the Krypton SPT-40M experimental model was chosen equal to 39 mm.

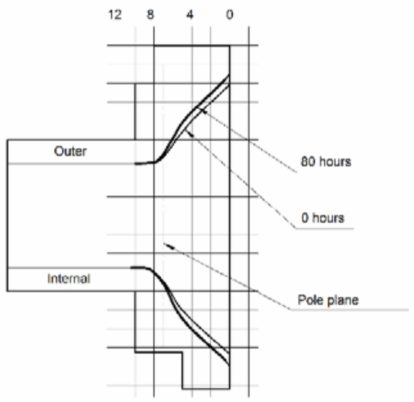


Figure 4 - The wall profiles after 80-hour SPT-100VT-EM erosion tests

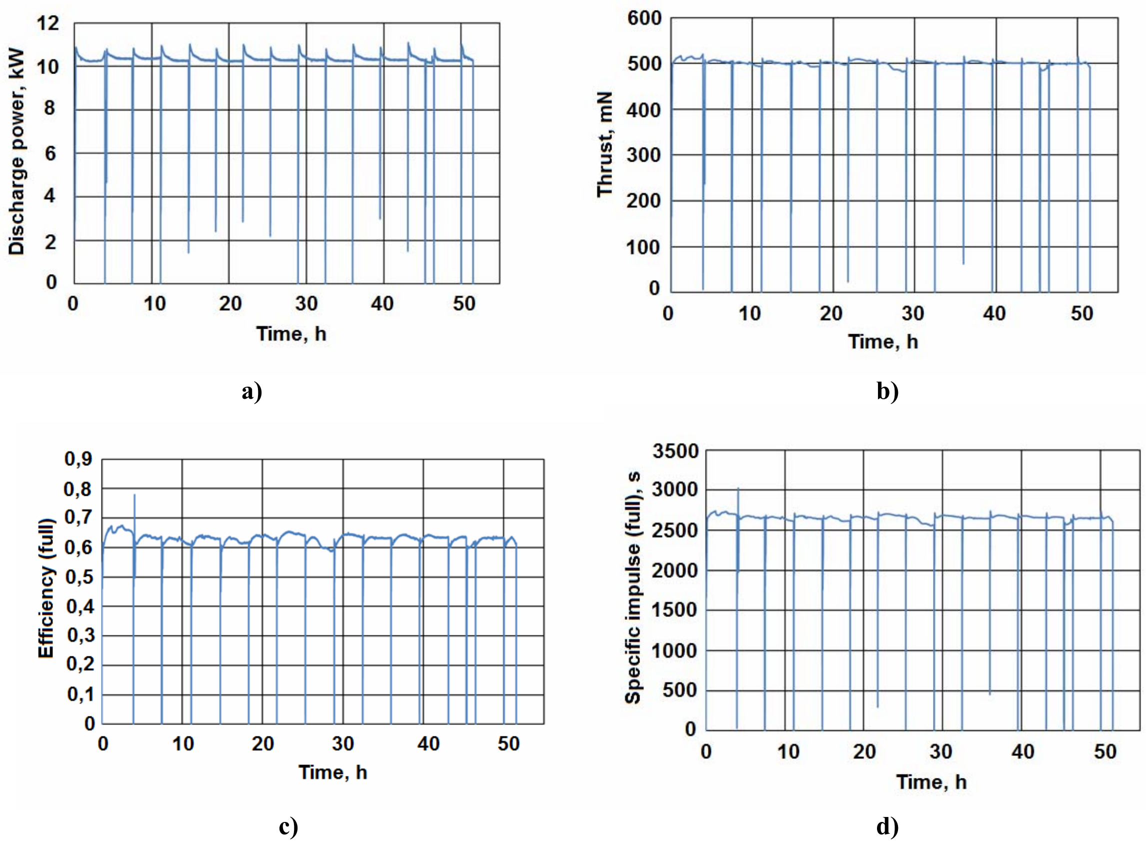


Figure 5 - The SPT-140 PM parameter variation in time diuring its erosion test.

Then, in this model it was used the magnetic system allowing getting of notable shift of the magnetic induction longitudinal distribution maximum out of the magnetic poles plane (Figure 6). The exit part of the acceleration channel was widened by 30 degrees at each wall in the space outside of the magnetic pole plane. So, one could expect that erosion zone, if they are positioned in the widened channel part, are to be there during the model long operation and further channel widening.

And it was interesting to check the performance of the developed SPT-40M model and to determine the positions of the wall erosion zones while it is operating with Krypton and Xenon. Results of this model characterization and erosion tests are represented in the next part of the given paper.

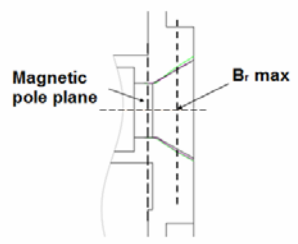


Figure 6 - Exit part of the SPT-40M acceleration channel.

B. Results of the SPT-40M performance investigations and erosion test

The SPT-40M model was tested in the ranges of the mass flow rates through the acceleration channel 0,8-1,2 mg/s of the Xe and Kr and discharge voltages 200-300 V in the vacuum chamber of 2 m in diameter and up to 3m in length. Vacuum chamber was pumped out by the "dry" root pumps and high vacuum cryogenic pumps ensuring the dynamic pressure not higher than 1×10^{-5} Torr according to gauges calibrated for air. The Fakel LaB_6 cathode was used during this investigation with mass flow rate of Xenon or Krypton ~0,1 mg/s. Further the voltage-current characteristics of the SPT-40M operating with Krypton and dependences of the total (calculated taking into account the cathode mass flow rate and only the discharge power N_d) thrust efficiency and specific impulse are represented in Figure 7. All these characteristics of the SPT-40M operating with Krypton are typical for the KrSPT operating with low powers (Figure 7).

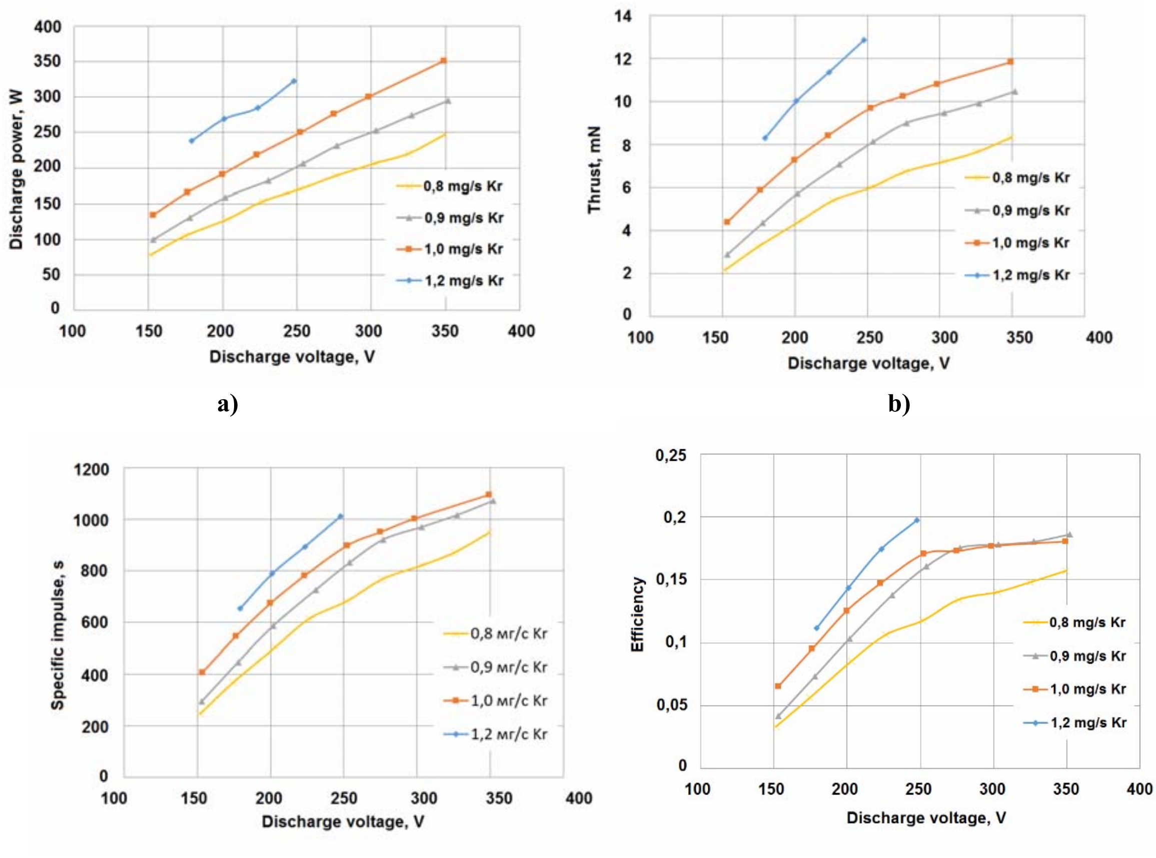
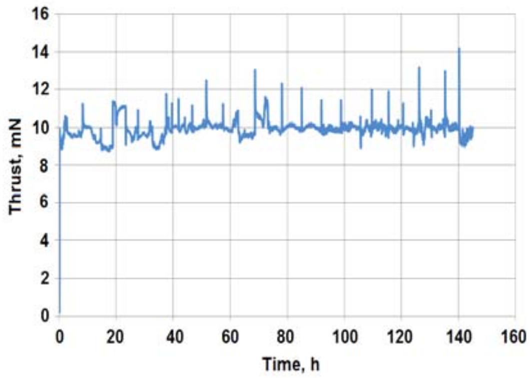
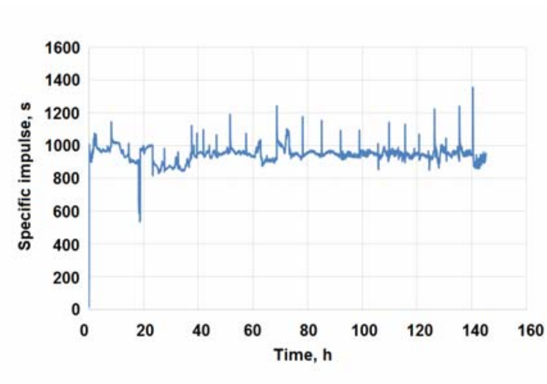


Figure 7 – Characteristics of the SPT - 40 M model operating with Krypton.

Obtained results show that the chosen thruster size is still too great because the thrust efficiency of the SPT-40M model operating with mass flow rates ensuring power around 250W do not exceed 20% and with increase of the mass flow rate thrust efficiency is increased. An another reason for the low KrSPT-40M thrust efficiency is the mentioned earlier difficulty to create optimal magnetic field in its discharge. Indeed the SPT-50 thruster of the increased scale demonstrates a little bit higher thrust efficiency (see Figure 1). Nevertheless it was interesting to estimate prospects of obtaining large enough life time of the KrSPT-40M because even for KrSPT-50 of typical design obtaining of 5000 hour or larger life time is problematic. Therefore there was made 150-hour erosion test of the SPT-40M model operating with Krypton. During the first 40 hours of this erosion test there were made optimizations of the operation mode and the last 100-hours SPT-40M model was operating with the chosen operation mode parameters: discharge voltage (255V, total mass flow rate 1,05 mg/s ensuring power (230-250)W, thrust (10 ± 1) mN, thrust efficiency (0,17-0,20) and specific impulse (950 ± 50) s (Figure 8).

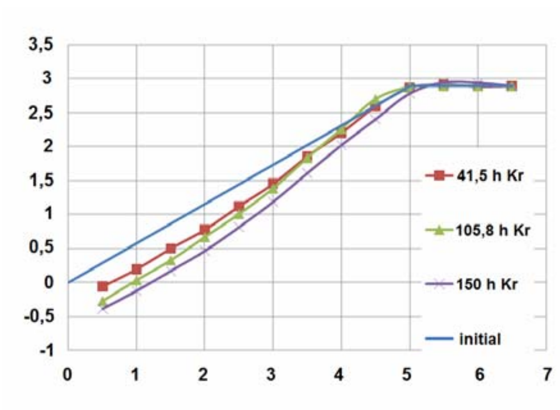


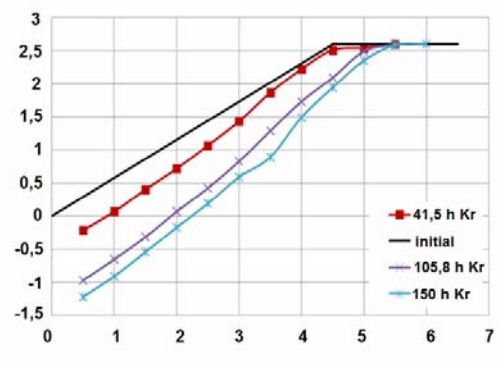


a) **b)**

Figure 8- SPT-40M parameters during erosion test.

Results of this test had shown that the erosion zones were almost fully positioned in the widened exit part of the acceleration channel (Figure 9) and erosion rates allows prediction of KrSPT-40M life time over 3000 hours at least. Therefore the next step is to be the further optimization of this model design to improve its performance level.





a) **b)**

Figure 9 - The SPT-40M external and internal wall profiles before and after erosion test

It is worth to note that this model was tested also with Xenon including its 100 - hour erosion test and mean values of its parameters during erosion test are represented in the Table 1. Obtained efficiency and specific impulse are comparable with performance data of the SPT-50 serial thruster and erosion rates are also allows prediction of a large life time of the XeSPT-40M model operating with the discharge power around 200 W. Thus, the developed model seems as prospective enough.

Table 1. Parameters of the SPT-40M and some other low power SPT's operating with Xe.

SPT model company	Discharge voltage, V	Discharge power, W	Mean thrust, mN	Mean Isp, s	Anode thrust efficiency	Expected life time, hours
SPT-40M RIAME	225	195	12,0	1050	0,33	5000
Plas40 Fakel [17]	160	200	14,5	820	0,35	5000
CAM200 ASRI [18]	?	190	10,3	1400	0,37	1000
HT-200(?) Sitael [18]	?	190	10,4	1360	0,36	?

Obtained efficiency and specific impulse are comparable with performance data of the SPT-50 serial thruster and other low power SPT's [2]. The main advantage of the developed SPT-40M and Plas40 models is the larger their expected life time in comparison with other low power thrusters operating with the discharge power around 200 W with Xe. Similar conclusion could be made on the SPT-40M model operating with Krypton and power ~250W. Thus, the developed model seems as a prospective enough.

III.Conclusion

As a whole obtained results shows that an applied approach promises at least the possibility to obtain the large life time of the low power SPT developed on base of the SPT-40M model and confirm the possibility to develop on base of the SPT-40M a competitive lower SPT operating with Xe and Kr with acceptable performance level and large enough life time with powers 200W and 250 W, respectively. Therefore it is reasonable to continue optimization of the developed model design and its operation to increase its thrust efficiency.

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