OPERATION PECULIARITIES OF HALL THRUSTER WITH POWER 1.5 – 2.0 kW AT HIGH DISCHARGE VOLTAGES

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ABSTRACT

The peculiarities of Hall thruster work with power 1.5 – 2.0 kW at high discharge voltages are discussed. Thruster operation mode with specific impulse 3000 s was obtained in this power range. The peculiarities of accelerating channel walls sputtering of Hall thruster working at high discharge voltages were studied out. The analysis was carried out basing on comparison of insulator material sputtering rate in two thruster operation modes with equal power (1,5 kW) but different discharge voltages (300 V and 670 V). The comparison of thruster expected lifetime working at these two operation modes was done. It was found out that the sputtering rate depends on discharge power. The thruster KM-100 was developed and tested. Practical opportunity of thruster lifetime considerable increase at high voltage operation mode was determined. Preliminary estimations showed that thruster expected lifetime with discharge power 2.0 kW and specific impulse 3000 s is up to 6 – 8 thousand hours.

INTRODUCTION

The increasing of communicational spacecraft (SC) lifetime leads to the necessity of raising the consumption of characteristic velocity, necessary, in particular, for the SC station keeping in geostationary orbit (GEO). Moreover, the increase of propulsion system (PS) total impulse is sometimes determined by the increase of SC mass. All this stimulates the application of electric propulsion systems (EPS) with high specific impulse in the PS structure of SC orbit adjustment for decreasing of required propellant and increasing of payload mass.

In Keldysh Research Center (KeRC) works on development of high efficiency EPS with specific impulse up to 3000 s are held. The thruster operates on xenon. These works are held in order to develop PS for solving the problem of orbit adjustment of prospective geostationary SC.

On the first stage of works the practical probability of high efficiency and high specific impulse thruster development was determined. X-85M thruster model was tested on discharge voltages up to 750 V in power range from 1 to 2 kW. We obtained the thrust of 85 mN at power of 2010 W and xenon flow rate through anode – 2,7 mg/s at one of the operation modes. Taking into account the flow rate through cathode (0,1 mg/s) and the power used for cathode operation maintenance and magnet field generation the specific impulse and efficiency were 3100 s and 64% respectively[1]. So the possibility of high efficiency operation mode realization was proved for the thruster xenon flow rate, which is not optimal for this power level.

The purpose of the second stage was to provide long lifetime of the thruster working at high discharge voltage values. In particular, for 3000 s specific impulse creation discharge voltage at 700 – 1000 V level may be needed. This is more than 2,5 times greater than traditional level of discharge voltages for stationary plasma thrusters (SPT) (300 V). The discharge voltage increase may cause the increase of insulator rings sputtering rate at anode chamber exit and, as a result, thruster lifetime decrease.

For investigations of insulators material sputtering rate at high and traditional voltages the thruster X-85M was used. It is designed for operation at power up to 2 kW and discharge voltages up to 1000 V.

The thruster KM-100, which is developed taking into account the experience of works with X-85M thruster, is being tested in KeRC now. One of the main problems to solve is ensuring the thruster lifetime at level of 6 – 8 thousand hours[2]. The thruster KM-100 is also designed for work at high discharge voltages.

EXPERIMENTAL STUDY OF INSULATOR SPUTTERING RATE

The X-85M Hall thruster is developed for power level of 1,5 kW. Its description could be found in Ref. 3. Middle diameter of the acceleration channel is 85 mm.

The dependence of insulator material sputtering rate from the thruster operation mode was studied during experiments. The discharge voltage was about 300 V at the first mode and the thruster operated at high discharge voltage (about 670 V) at the second mode. The operation time for both modes was 25 hours of net time with shot stops for thrust measurements every 2-3 hours. Basic thruster parameters during these experiments were changing in limits that are shown in table 1.

Table 1

m_a, mg/s	U_d, V	I_d, A	N_d, W	R, mN	$I_{sp.}$(tot.),s	Efficiency (tot),%	$T_{body.}$, °C	$\Theta_{95\%}$, degrees	$P_{chamber}$, torr
5	304 – 316	4,65 – 4,69	1450 – 1510	93 – 98	1860 – 1960	56 – 63	170 – 200	63 – 66	$2,2*10^{-4}$ – $2,7*10^{-4}$
2,3	660 – 690	2,10 – 2,19	1490 – 1510	65 – 66	2800 – 2930	59 – 61	190 – 210	51 – 56	$1,1*10^{-4}$ – $1,4*10^{-4}$

Residual pressure in the chamber was $1,3*10^{-5}$ – $1,4*10^{-5}$ torr. Xenon flow rate through cathode was 0,1 mg/s.

Discharge current and additional power, used for cathode and magnets, slightly changed during the thruster warming up, so to provide constant level of consumed power we had to regulate discharge voltage.

However, these changes were in rather narrow range. Both experimental series were carried out without any unplanned stops or discharge disruption. This testifies reliability of thruster work at high voltage mode.

The thruster body temperature (the thermocouple was placed on back plane of magnetic circuit, 50 mm far from the thruster axis) was 200°C and insignificantly differs for two studied modes. This indirectly proved that the temperature of magnetic circuit and magnetic coils did not exceed the maximum permissible values for materials used. The inner insulators of accelerating channel did not emit visible radiation when they reached thermal equilibrium state. This proved that the surface temperature did not exceed 500°C. The insulator surface temperature increase leads to the increase of sputtering rate for fixed ion flow[4]. If surface temperature exceeds 650°C the sputtering rate begins to grow quickly. This negatively affects on thruster lifetime.

The plume divergence ($\Theta_{95\%}$,) at 95% current level was measured 45 cm far from the thruster cut. It is shown in table 1 that for high voltage mode the divergence is better than for traditional mode. This indicates that at high discharge voltages the plume is formed better at thruster exit.

However, the main purpose of experiments was the comparison of profiles of inner insulators that experience the most violent sputtering during thruster work. For this purpose two identical insulators were manufactured. Their basic profiles were preliminarily measured. The identity of the insulators was also proved by their weighting. The difference among the insulators' weights was less than 0,2%. The profiles of the insulators were also measured after they had been worked for 25 hours. These results are shown in fig.1.

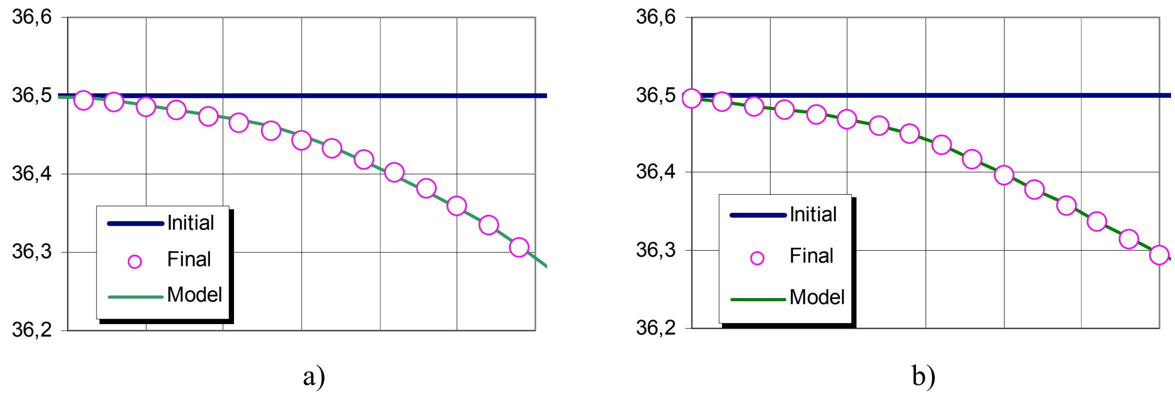


Fig. 1. X-85M inner insulator profile changing after 25 hours of operation at discharge voltage a) 300 V, b) 670 V.

THE METHOD OF INSULATOR SPUTTERING RATE STUDY

Basing on obtained experimental data of sputtering rate the numerical forecast of the thruster lifetime for two operation modes was done (traditional mode – discharge voltage is about 300 V, and high specific impulse mode - discharge voltage is about 670 V). As the basis of computation method of insulator surface profile change during thruster work the following assumptions are made:

- ion flow on channel walls could be imagined as the flow from a point source, which is placed on the border of erosion zone at some height above the channel wall;

- plume divergence of ion energy flux for thrusters of the same type could be described with a help of universal function in non-dimensional coordinates;
- dimensional scale coefficient of energy flux real distribution is defined by the discharge voltage, discharge current and acceleration channel geometry;
- the position of simulated ion source could be changed during thruster operation due to the changes of acceleration channel geometry;
- the factor of energy flux real distribution and the ion source position could be determined with the help of short lifetime tests.

Experimental dependences of sputtering coefficient from hade and ion energy that were used in calculations are taken from Ref. 5.

The measurements of insulator surface profile were made with the help of special designed facility, which provides measurement error in radii direction not more than 20 μm. The insulator surface profile was measured by contact method with the help of multiturn detecting head. The detector sensor was a special made brass needle. The needlepoint was made not to damage the insulator surface and, at the same time, to provide the sufficient accuracy of measurements. The main soften influence that protected the surface from damage during the measurements is made by shock-absorbing detector mechanism. It allows putting needle down very fluently on the surface. Moreover, while moving along the insulator the needle did not touch its surface. Tests showed that there are no any traces on the insulator surface after the needle that exceed the depth of natural surface roughness.

The detector movement along the thruster axis could be made with accuracy up to 5 μm.

The measurements were made on generatrix of a sample – 0, 120, 240 degrees (the zero angle corresponds to upper insulator point when the thruster is placed in vacuum chamber) with 0,5 mm step along the surface. The data obtained was used in model, which forecasts the thruster lifetime.

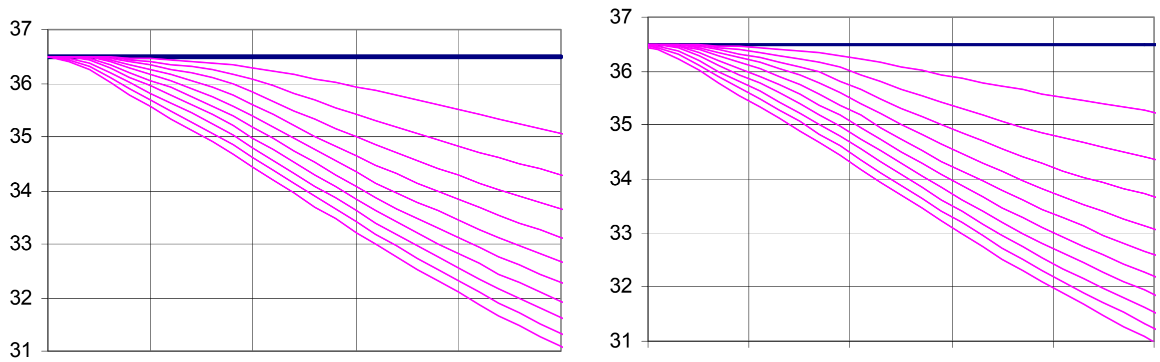
THE FORECAST OF THRUSTER LIFETIME AT THE INCREASED DISCHARGE VOLTAGES

The comparison of insulators profiles after operation at different thruster operation modes and using of the sputtering process simulation technique allows making a number of conclusions.

As is obvious from the fig.1, inner insulator sputtering rate at discharge voltage 670 V was approximately equal to that at 300 V. In our opinion the explanation of this fact is that the sputtering rate of insulator material increases with increasing of incident ions approximately arcwise[5], while the density of spraying flow under constant discharge power also decreases arcwise with increasing of the discharge voltage. Thus the total energy flux of ions falling on the insulator surface remains constant with discharge voltage increasing. These arguments are valid for comparable values of thruster efficiency.

A number of computations using the numerical model have been made for investigation of the insulator sputtering rate. In calculations the position of simulated ion point source position was chosen to fit experimental profile with calculated one in the best way. The results of calculations are presented in fig. 1. It is important to note that in both operation modes good coincidence between calculations and experiments was achieved, while the mean energy of falling ions was chosen as the only variable parameter. Since the discharge power in both modes was equal, the obtained result confirms the assumption made above.

On the base of obtained numerical model parameters the forecast of further insulators sputtering for both modes has been made. The results of forecast are presented in fig. 2. These results were used for estimation of thruster lifetime at both operation modes. The hitting of sputtering ion flow on the inner magnetic circuit pole was chosen as the thruster lifetime limit criterion. As we can see from the obtained results thruster lifetime at discharge voltage 300 V and 670 V should be approximately the same at condition of the same erosion zone border placement.



a) b)

Fig. 2. The forecast of the X-85M inner insulator profile changing during 1000 hours (profiles are shown with 100 hours timestep) at discharge voltage a) 300 V, b) 670 V.

In KeRC KM-100 thruster was developed and tested. KM-100 thruster was designed for nominal power 2,0 kW and discharge voltage up to 1000 V. The middle diameter of accelerating channel is 100 mm. The main attention during development of thruster construction was made on achievement of 6-8 thousand hours lifetime.

The first experimental results with KM-100 on high specific impulse operation mode allowed defining the erosion zone placement. These data were used in numerical model for estimation the possible character of inner insulator profile changing. In calculations such angle distribution for ion energy flux density was set that good coincidence of experimental and computational results as for X-85M thruster as for KM-45 thruster was achieved. These thrusters have the similar configuration of the accelerating channel. The results of calculation are presented in fig. 3.

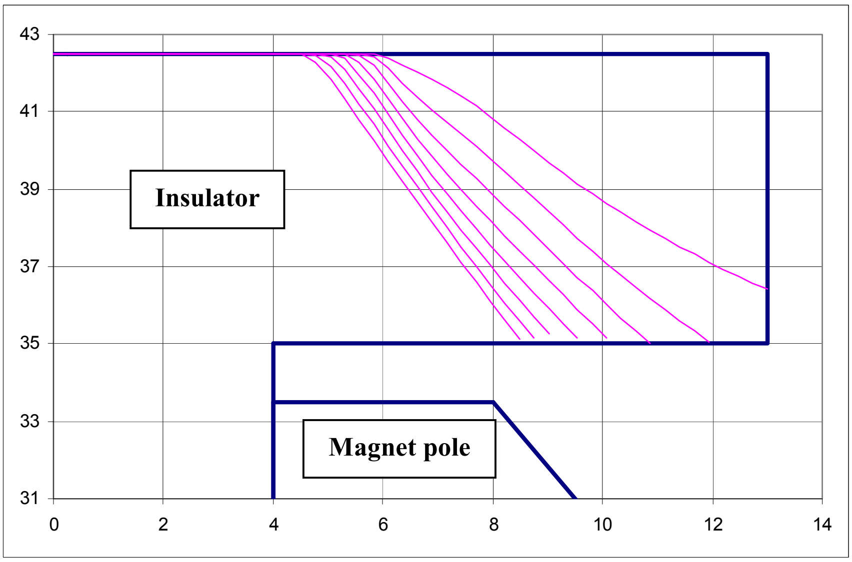


Fig 3. The forecast of KM-100 inner insulator profile changing during 8000 hours (profiles are shown with 1000 hours timestep).

The KM-100 thruster construction allows to provide high lifetime at high specific impulse operation mode. The estimation done allows to hope for lifetime not less than 6-8 thousand hours.

CONCLUSION

1. The lifetime abilities of X-85M thruster at high specific impulse operation mode were tested. The study was based on direct comparison of channel walls material sputtering rate during the thruster operation at two modes – traditional, with discharge voltage of 300 V, and high specific impulse mode at 670 V. We found out that the insulator sputtering rate was almost equal for both modes. The conclusion is done that the sputtering rate basically depends on discharge power.
2. KM-100 was developed and tested. This thruster is designed to operate at high specific impulse.
3. The estimation of KM-100 thruster lifetime at high specific impulse mode is done. The expected lifetime is not less than 6 – 8 thousand hours.

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