INVESTIGATION OF THE STATIONARY PLASMA THRUSTER (SPT) OUTGASSING AND ITS THERMAL STATE IMPACT ON THRUSTER PERFORMANCE VARIATION IN TIME

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Abstract

During the stationary plasma thruster (SPT) performance investigation, acceptance and other tests as well as during the first SPT firings and its cyclic operation in space there are some particularities in the thruster performance variation in time after thruster switching on. Therefore it is interesting to understand the reasons having an impact on the thruster performance variation in time during the first hour at least after thruster operation starting. These reasons depend on concrete thruster history, but for every thruster some one has to consider:

- thruster structural element outgassing in a vacuum conditions,
- thruster thermal state variation due to its heating after starting,
- change of the discharge chamber (DC) internal surfaces state due to their plasma flow processing after thruster operation starting,
- DC and anode internal surfaces contamination at least by material sputtered from the DC walls,
- Change of the accelerating channel geometry due to DC wall erosion.

Two last reasons are changing the thruster performance during ten and hundred hours and had been studied earlier. Therefore other reasons having an impact during ~1 hour after thruster switching on was studied.

To realize this study PPS-1350 laboratory model was equipped by additional heaters and thermocouples to control thruster thermal state. Then the thruster performance variation in time had been studied when thruster had different initial state. Results of experiments show that under modern SPT starting procedure and stationary operation mode parameter control:

- the thrust is reduced during ~1 hour due to thruster outgassing if before starting thruster was exposed to atmosphere;
- thrust is varied within (2-3)% during the first (10-20) minutes after thruster switching on due to its heating by discharge.

Using obtained data it is possible to reduce the thruster performance variation in time after its switching on, if necessary.

Introduction

As it is well known [1], the so-called stationary plasma thruster (SPT) are used in a Russian Space Technology already many years. And there

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were observed some particularities in a temporal behavior of its performance. The long term variation of thruster characteristics was studied during at least several lifetime tests [2,3]. But there was no great attention paid to the relatively short term performance variation in time while typical duration of thruster operation onboard geostationary satellite is ~1 hour per 1...3 days. So, it is interesting to study SPT characteristics behavior within ~1 hour of operation after its switching on. Having these data it is possible to correct thruster operation during its ground tests or during its operation in space, if necessary.

Therefore within the frames of the PPS-1350 type SPT development efforts of SEP and design bureau Fakel supported by RIAME there was studied the temporal behavior of the SPT characteristics variation in time and possible reasons able to have significant impact on the mentioned behavior.

1. Analysis of possible reasons of the SPT performance temporal variation

SPT performance as that one of each space technology element depend on its design features and history, namely: on materials and the conditions of its part manufacturing, assembling and further storaging before thruster test (if some one consider the ground tests), on the conditions of the thruster integration into propulsion subsystem (PS), PS storaging and assembling onboard Spacecraft (S/C), S/C storaging conditions before launch and its history before thruster is switched on. Surely it is necessary to know an impact of all the mentioned conditions on the thruster performance, including its temporal behavior. There are a lot of physical factors able to have definite influence on the thruster operation and its performance temporal variation within ~ 1 hour time frame after thruster switching on such as:

- thruster structural element outgassing in a vacuum conditions (in a vacuum chambers during the ground tests or in space during its onboard operation);
- thruster element thermal state variation due to its heating after thruster switching on;
- change of the thruster structural element surfaces state due to their contamination and interaction with the plasma flow (experience coupled during the SPT tests shows that the most sensitive are the contamination of the anode and discharge chamber wall surfaces);
- variation of the thruster elements geometry due to their erosion as a result of thruster prolonged operation (results of the SPT lifetime tests show that for SPT the most intensive is the erosion of the discharge chamber walls by the accelerated plasma flow).

As it was mentioned the consequences of slowly going processes such as the change of the discharge chamber wall geometry and contamination of walls by products sputtered from the end parts of discharge chamber were studied earlier. But there was no specific investigation of the thruster element outgassing and heating impact on the thruster performance and its variation in time as well as the impact of the discharge chamber wall surface state variation in time. It is necessary to add that by now there is no effective methodology to control the DC internal surface status. Therefore there was used registration of thruster integral parameters. Registration of the thruster element thermal state is more simple task. It was realized using general thermocouples.

The characteristic period of thermal transient processes is different for the different parts of thruster. Typically the most heated parts of thruster are the exit ends of DC walls. They are connected with the other parts of DC by the relatively thin walls having low thermal conductivity. Therefore it is possible to estimate the temperature of these parts taking into account only thermal radiation, e.g. using the equation:

$$cm\frac{dT}{d\tau} = Q_W - \varepsilon\sigma_0 S\left(\frac{T}{100}\right)^4, \qquad (1)$$

where *cm* is the end part thermal capacity (*m*- is mass of this part),

Q_W – thermal flow to end part from discharge,

ε, σ_0 – thermal radiation factors,

S - end part radiating surface area,

T – temperature,

τ - current time.

Solution for this simple equation is

$$\frac{1}{4a^3}\ln\frac{(a+T)(a-T_0)}{(a-T)(a+T_0)} + \frac{1}{2a^3}\left[arc\,tg\left(\frac{T}{a}\right) - arc\,tg\left(\frac{T_0}{a}\right)\right] = $$
$$= b\tau, \qquad (2)$$

where $a = 10^2\sqrt[4]{\frac{Q_W}{\varepsilon\sigma_0 S}} = T_\infty$ - is ultimate temperature of part under $\tau \to \infty$,

$$b = \frac{\varepsilon\sigma_0 S}{10^8 cm} \qquad (3)$$

Analysis of the expression (2) shows that the temperature of element grows in time under fixed Q_W almost linear till $T \approx 0{,}8T_\infty$. Therefore it is possible to estimate the characteristics transient time as

$$\tau_1 \approx \frac{cm\Delta T}{Q_W}, \qquad (4)$$

where ΔT – is the temperature difference between initial and final status. Using these expressions it is possible to obtain τ_1 values ~(5-7)minutes and T_∞~870K under Q_W equivalent to ~0,1N_d, where N_d is discharge power, for two end parts of DC and ΔT=(400-500)K, for the SPT-100 or PPS-1350 type thrusters under N_d~1,35kW. Similar results could be obtained for the anode temperature variation.

For the magnetic system elements the duration of transient processes is significantly larger due to their higher mass, larger surface area and lower Q_w value.

Obtained results show that the outgassing could be significant in a some minutes after starting due to high temperature of anode and discharge chamber. For typical SPT design it is possible also that at least internal magnetization coil could release to the DC exit portion of gases absorbed by the porous insulating cover of wire. In addition magnetic system thermal state variation could cause the change of some linear thruster element sizes and part relative positions.

Thus the magnetic system and DC heating even under fixed magnetization currents could cause some changes in the magnetic field intensity and its distribution inside the accelerating channel due to the variation of magnetic material permeability and thruster element sizes and their relative position. Typically SPT is designed to minimize these changes. Nevertheless it was interesting to study the possible impact of all the mentioned factors on the thruster performance variation in time.

The outgassing could cause the thruster performance change due to the appearance of gas impurities in a main propellant (xenon) flow. If this flow is great enough it will cause some performance deviation from that one for xenon. Roughly this could be explained by the following. If for example there is nitrogen or oxygen impurities under fixed Xe flow rate it will cause increase of discharge current due to impurity atom and molecule ionization. But efficiency of their ionization and acceleration is lower than for Xe. So, the total efficiency for the Xe with impurities will be lower than for the pure Xe case. In a modern SPT propulsion subsystems there is used the discharge current stabilization. In this case appearance of impurities will cause decrease of Xe mass flow rate and decrease of thrust under fixed power. Thus it is necessary to know the scales of outgassing impact on the thruster performance.

2. Methodology of investigation

To investigate the outgassing and thruster element heating influence on the thruster performance there were studied their variation after thruster starting for the following cases:

1. "Cold" (room temperature) thruster exposed to atmosphere during several days.
2. "Cold" thruster outgassed by the previous preheating in a vacuum or by the steady state operation during some hours and the consequent cooling in a vacuum.
3. "Warm" thruster preheated by the specific heater or by operation during at least 1 hour.

Study of the performance variation for these cases allowed to divide the outgassing and thermal state variation impacts.

To realize this study the RIAME PPS-1350 laboratory model was equipped by an additional heaters (Fig. 1a) and thermocouples (Fig. 1a, 1b) to measure anode temperature in a two points positioned at opposite sides of the anode as well as the temperatures of the external and internal discharge chamber wall exit parts (in a one point for each wall). Number of thermocouples was limited due to the necessity to pass the corresponding wires through thrustmeter.

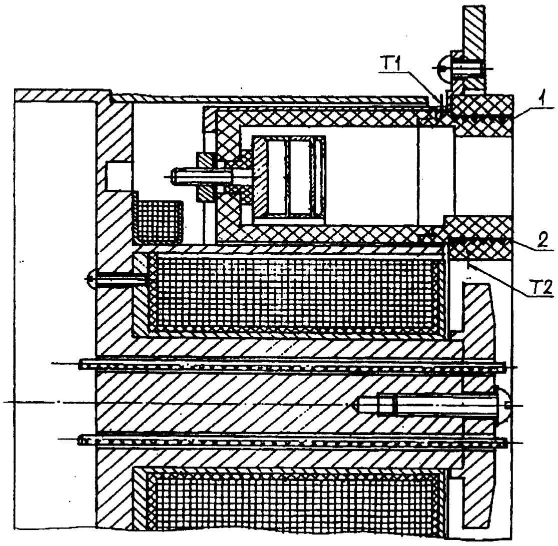

Fig. 1a. PPS-1350 laboratory model design diagram
1, 2 - heaters, T1, T2 - thermocouples

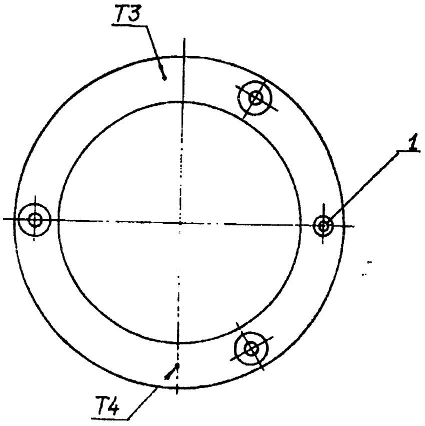

Fig. 1b. Anode thermocouple positioning scheme
1 – gas feeding tube, T3, T4 - thermocouples

Then to get more reliable temperature measurement and to protect registering and data processing computer there was introduced an additional galvanic isolation of registering circuits. Data registering computer program was fixing data automatically.

A test was done using test facility with the vacuum chamber of 2 m in diameter and 6 m in length. The dynamic pressure inside vacuum chamber during tests did not exceed $1{,}5\cdot 10^{-4}$ Torr.

Test procedure was relatively simple: starting from different thruster state there was registered the thrust, discharge current and thruster element temperature values under fixed mass flow rates through the anode and cathode and fixed magnetization currents.

The magnetization current values has been chosen optimal for steady state thruster operation mode with discharge voltage U_d=350V and discharge current $I_d \approx$ 4,2A (N_d ~1450÷1500W).

Due to the whole experimental unit thermal state change after thruster starting causing the thrustmeter zero drift there was made special startings to investigate the mentioned drift law. This law was introduced to the computer program. Additionally some checkings of "zero" has been made during experiments also.

Concrete program of tests consisted of:

A. Starting of "cold" thruster exposed before test to atmosphere during ~ 5 days;
B. Starting of the preheated in a vacuum during ~ 2 hours and "warm" due to this preheating thruster; preheating gave an anode temperature T_a~500C, DC wall exit part temperatures T_w =(500-650)C; before preheating thruster was exposed to the atmosphere during ~ 3 days;
C. Starting of outgassed and preheated thruster being ~ 11 hours under root vacuum conditions (pressure in a chamber P_c ~10^{-1} Torr);
D. Starting of the outgassed "cold" thruster; outgassing was made by preheating and thruster operation during ~ 1 hour under nominal operation mode with power N≈1500W (discharge voltage U_d ≈350V); taking into account long duration of thruster cooling there was used the cooling procedure consisting of its ~13,5 hours keeping in a vacuum conditions (P_c ~ 10^{-5} Torr).

3. Results of experiments

Obtained results show that:

A. For the starting of the "fresh" (exposed to atmosphere during 5 days) cold thruster (having room temperature) the thrust and discharge current values are reduced during the first ~ 5 minutes (Fig. 2). Then the thrust value is slightly increased till initial value. Discharge current is stabilized after the first 10 minutes and then don't change significantly; the thrust variation is within 5%, discharge current variation is within 7%. The temperatures of anode and discharge chamber walls are changed rapidly during the first 10 minutes and by the end of the first hour get the level of T_a ~(500-550)C and T_w ~(400 - 450)C respectively.

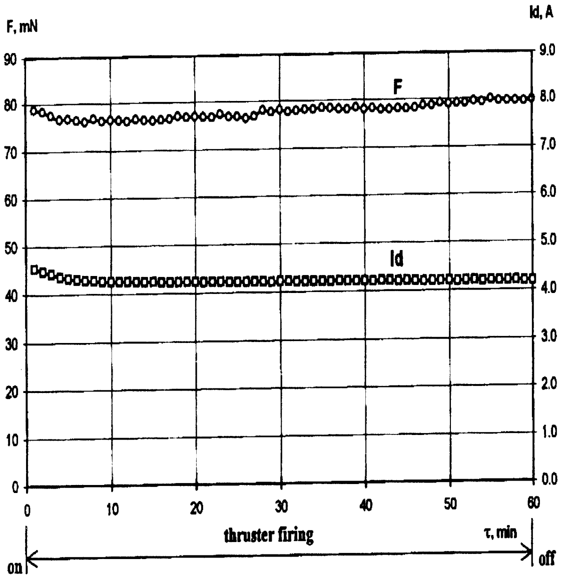

Fig. 2a. Thrust and discharge current variation in time for the "fresh" cold thruster

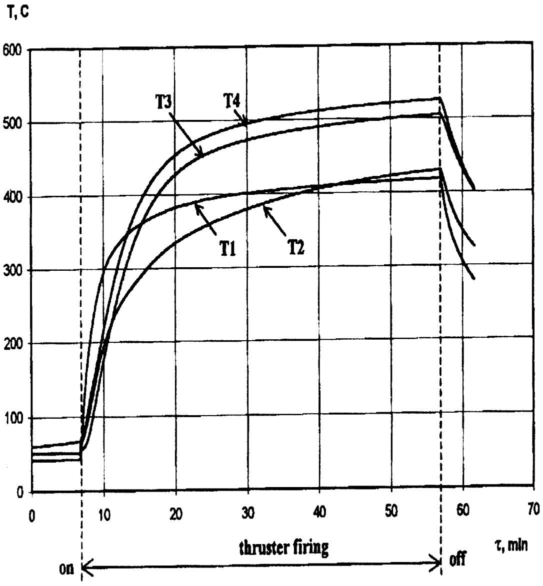

Fig. 2b. Anode and discharge chamber wall temperatures in time

B. For the starting of the "fresh" (exposed to atmosphere during ~ 3 days) thruster preheated in a high vacuum (vacuum chamber pressure during preheating was less than $5\cdot 10^{-5}$ Torr) there is no significant changes of thrust and discharge current values during the whole 1 hour cycle of thruster operation (Fig. 3). The thruster starting has been realized, when anode temperature was at the level of ~400C and discharge chamber wall temperature at the level of (300-400) C (Fig. 3b). As one can see the main difference of two considered cases is the initial thrust and discharge current decrease during the first 5-7 minutes in the case of the "fresh" and "cold" thruster and absence of such decrease for the outgassed and "warm" thruster. Besides there is definite thrust increase after the first 10 minutes for the "fresh" and "cold" thruster starting.

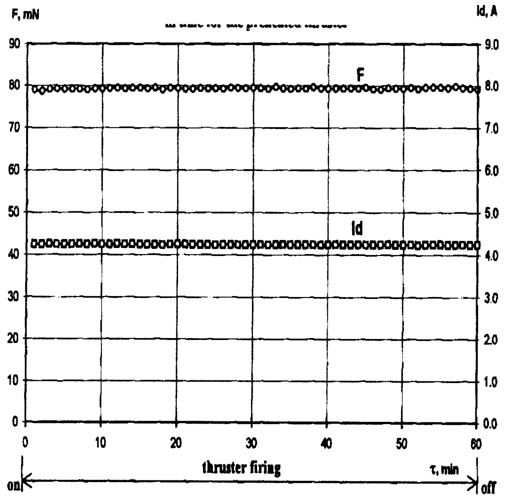

Fig. 3a. Thrust and discharge current variation in time for the preheated thruster

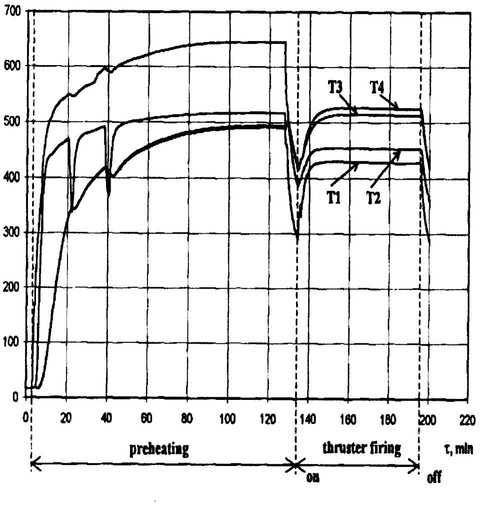

Fig. 3b. Anode and discharge chamber wall temperatures in time

C. During the starting of the outgassed and "warm" thruster being in a root vacuum conditions during ~11 hours thrust and discharge current were also almost stable.

D. After starting according to the point C thruster was cooled during 13,5 hours (to ensure full cooling) in a high vacuum (p_c ~10^{-5} Torr) conditions and after cooling has been switched on. Obtained results show that again there is definite decrease of thrust and discharge current during the first (5-7) min of thruster operation.

Taking into account that discharge current is changed in time it seems useful to consider the thrust F to discharge current I_d ratio, because during real starting procedure discharge current $I_d \approx$ const and for startings of cold thruster the mass flow rate is reduced by control system to maintain $I_d \approx$ const. To simplify a comparison in Fig. 4 there are presented the F/I_d ratio divided by its maximal value during 1 hour for each case.

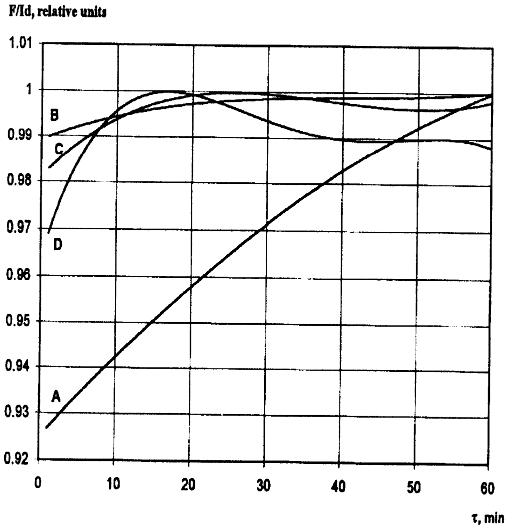

Fig. 4. Thrust to discharge ratio versus time

A. "Fresh" cold thruster
B. Preheated thruster
C. Preheated thruster
D. Outgassed "cold" thruster

Obtained data allows to conclude that:

- For the preheated (and therefore outgassed) thruster there is no significant variation of F/I_d ratio (or thrust under I_d=const);
- For the outgassed thruster (case D) the main reason of thrust variation during 1 hour cycle is the change of thruster thermal state;
- The outgassing reduces the thrust level for the starting of "fresh" and "cold" thruster (see cases A and D) during ~1 hour of operation at least.

Thruster thermal state impact on the performance variation could be explained by nonoptimal magnetization current values for the different thruster thermal states after its starting.

Conclusion

The data presented in a report shows that;

• anode and discharge chamber outgassing reduces the thrust during the 1-st hour of the "fresh" (exposed to atmosphere) thruster operation;

• for cyclic operation of the outgassing thruster the thrust variation in time is caused mainly by change of thruster elements thermal state.

References

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