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Investigation of a Low-power Thruster on Krypton Propellant

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Abstract

Nowadays, higher requirements are set for modern spacecraft,and, in particular, those related to the cost-efficiency of the mission. To ensure a reasonably long period of active life (approximately 10-15 years), stationary plasma thrusters (SPT) are successfully used in propulsion systems. Xenon is the substantial part of the cost of the propulsion system, which is why this could be significantly reduced, were xenon to be replaced with an alternative propellant.
On this basis, and taking into account the perspectives for the creation of multi- satellite orbital constellations and the tendency towards spacecraft miniaturizations, there is a demand for the development of a low-power thruster using an alternative propellant to Xenon. It is assumed that krypton is the most suitable replacement, albeit while using krypton there is a considerable decrease in the SPT thrust parameters. Therefore, it is necessary to perform investigations which reduce the negative consequences related to the use of krypton as a propellant.

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Keywords: Stationary plasma thruster; Krypton; Xenon; Propellant.

1. Introduction

At the present xenon is used in stationary plasma thruster to create reactive thrust. Xenon is used due to its high specific performance in comparison with other inert gases. However, notwithstanding this advantage, there is a factor which can limit xenon usage and that is, limited production of xenon lead at a high price.

Xenon, as well as all noble gases, is a by-product of nitrogen and oxygen production. As the content of xenon in the air is negligibly small (Table 1) there is no added-value by building a special plant for xenon production. This is why the rate of xenon production is not growing in hand with the increase in demand, and is totally restricted by oxygen production. These factors have an influence on the price of xenon, and make it more expensive than alternative propellants.

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It should be noted that on spacecraft with the present SPT construction, the replacement of xenon with an alternative propellant, in particular by krypton, will not lead to a in reduction in the cost of the mission.

Table 1. The amount of gases in the air

Substance	Symbol	Mass percent
Nytrogen	N_2	75.5
Oxygen	O_2	23.15
Argon	Ar	1.292
Carbone dioxide	CO_2	0.046
Krypton	Kr	0.003
Neon	Ne	0.0014
Methane	CH_4	0.000084
Hydrogen	H_2	0.00008
Helium	He	0.000073
Xenon	Xe	0.00004

Growth in the quantity of spacecraft and the creation of numerous orbital groups could lead to a shortage of xenon. It is not possible to increase xenon production, but its demand can be considerably decreased. A perspective alternative for xenon is krypton.

2. Comparison of Xenon and krypton as a propellant for SPT

There are a variety of reasons for xenon usage. Xenon has high atomic mass – 131 amu, and relatively low ionization potential – 12.1 eV. In addition, the inertness of xenon is able to eliminate the defects in operational safety, which occurred with mercury and cesium usage. In addition, xenon can be stored in heightened density, making it possible to decrease tank volume.

Krypton seems to be a perspective propellant in missions where heightened specific impulse is required. When compared to xenon, krypton has lower atomic mass – 83.8 amu, but higher ionization potential – 14.0 eV. Both xenon and krypton are inert gases, and xenon may be used as a propellant in propellant storage and feeding systems already developed, without essential upgrading. High ionization potential exerts a bad influence on thruster efficiency, but a lower atomic mass can theoretically increase specific impulse by 25 %. It can be useful for spacecraft keeping on geostationary orbit, but for transfer operations it will significantly increase the time of interorbital transfer.

A change in propellant can be carried out only if this change ensures acceptable performance. This is why the given research was conducted showing the change in the low power characteristics due to transition from Xe to Kr.

3. Operational characteristics of an SPT-50M working on xenon and krypton

Parametric tests of the thruster were conducted on different modes both on krypton and on xenon. These tests showed that under bounded discharge power (approximately 200 W):

- The best propulsion parameters are registering using xenon with a flow rate through accelerator channel of ~ 1 mg/sec and heightened discharge voltages (up to 250-300 V);
- Using krypton the thruster gets a considerably lower value of propulsion, specific impulse and thrust efficiency.

Voltage-current characteristics of the thruster working on xenon have a classical character. Voltage-current characteristics of the thruster working on krypton are of a varied character (Fig. 1), but in comparison with operation on xenon, for krypton the displacement of the initial zone of discharge current, increasing towards higher voltages is typical, and the zone with higher values of discharge current is practically absent.

This is natural, as krypton ionization requires a higher electron energy, which grows with the increase in discharge voltage. Another factor is that the decrease in flow rate results in a decrease in plasma density in the accelerator channel, as well as in the growth of free atom path before ionization. This is why, one and the same value of atoms-to-ions conversion is achieved with higher electron temperature, which is realized under higher discharge voltages.

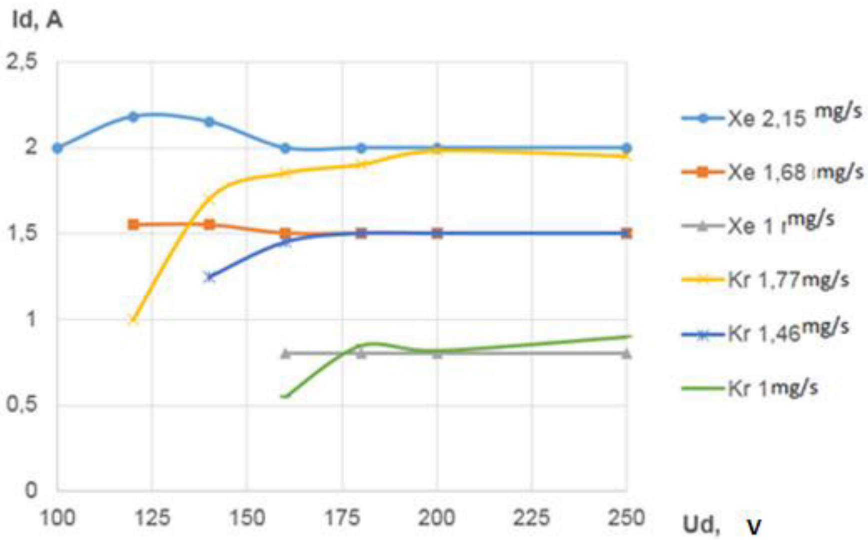

Figure 1. Voltage-current characteristic of the thruster working on xenon and krypton

Anode specific impulse dependency taken for SPT-50M running on xenon, shows that under direct voltage with xenon flow rate through the accelerator channel increasing more than 1.45 mg/s, the increase of specific impulse is insignificant (Fig. 2). This shows that plasma concentration in the indicated range is sufficient to achieve high atoms conversion in the accelerator channel by high discharge voltages. At the same time, when the thruster is running on krypton, increasing the flow rate up to a maximum value of 1.77 mg/s results in monotonic increase of anode specific impulse (Fig. 2).

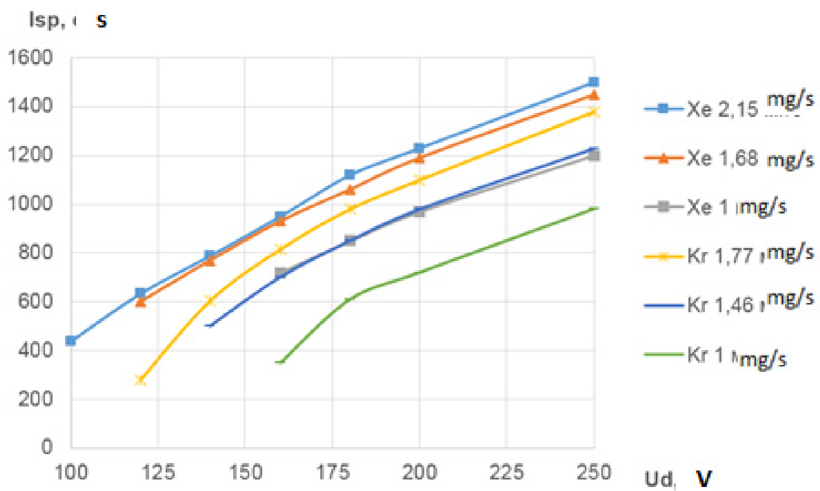

Figure 2. Anode specific impulse dependence on discharge voltage while working on xenon and krypton

In light of the aforesaid, it could be supposed that, even working on xenon with a small flow rate through the accelerator channel, as on krypton, at research mode the atoms-to-ions conversion coefficient would not be high. Possible ways of improving propulsion characteristics are to increase voltage and mass flow density. That is why for the design of the thruster, working on low power, it was decided to decrease the cross-section area of the discharge chamber by 1.5 times (as compared to the SPT-50M). This decrease allowed a new operating mode, which fits with SPT-50M operating mode with a discharge power of 250 W and a krypton flow rate of 1.5 mg/s. To provide the required cross-section area of discharge channel the width of – 8 mm, and outside channel diameter – 40 mm were chosen.

4. Development of SPT-40

4.1. Designing and parametrical testing of SPT-40

The construction arrangement of the thruster was designed according to the chosen dimensions (Fig. 3).

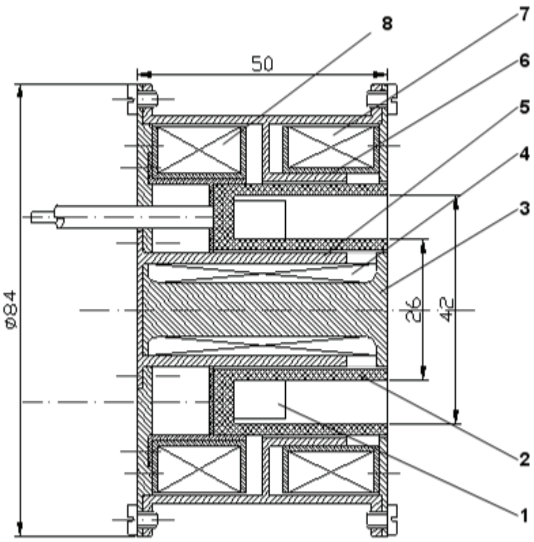

Figure 3. 1 – anode, 2 – discharge chamber, 3 – central core, 4 – central magnetic coil, 5, 6 – magnetic shields, 7 – main external magnetic coil, 8 – external ancillary magnetic coil

The thruster's magnetic system consists of magnetic shields (pos. 5 and pos. 6), a magnetic circuit and three magnetic coils: central coil, main external coil – the annular coil which covers discharge chamber, and external ancillary coil (pos. 4, 7, 8). The external ancillary coil was produced using previous experience in usage of the SPT-100 anode coil. The ancillary coil has to create an optimal magnetic field configuration in the accelerator channel and thereby raise thruster operating efficiency. There are some plug-in elements that allow the magnetic field topology to be managed. These elements are: the inner pole, which is fastened to the central core by screw and magnetic shield extensions. A plug-in magnetic shield extension allows the gap between magnetic shields and poles to be changed. The appearance of the laboratory model is shown in Figure 4.

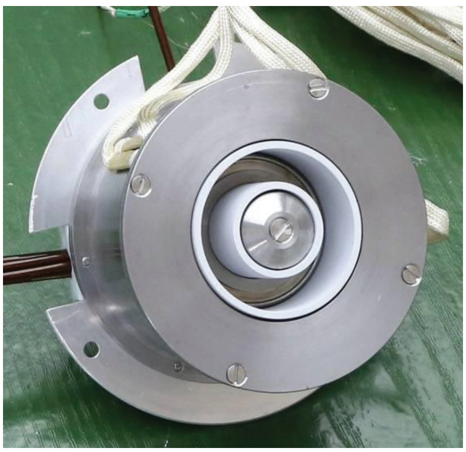

Figure 4. Appearance of the laboratory model

The Thruster's operating parameters were measured on an operating mode with fixed discharge current value at points 1.01 A, 0.92 A and 0.82 A, which corresponded to flow rates at values of 1.05 mg/s, 0.94 mg/s, 0.86 mg/s, respectively. As a nominal operating mode was chosen with discharge voltage at 300 V and current at 0.82 A, corresponding to a flow rate of 0.86 mg/s. In this mode thrust is equal to 10.1 mN (Fig. 5), and specific impulse 1212 s (Fig. 6).

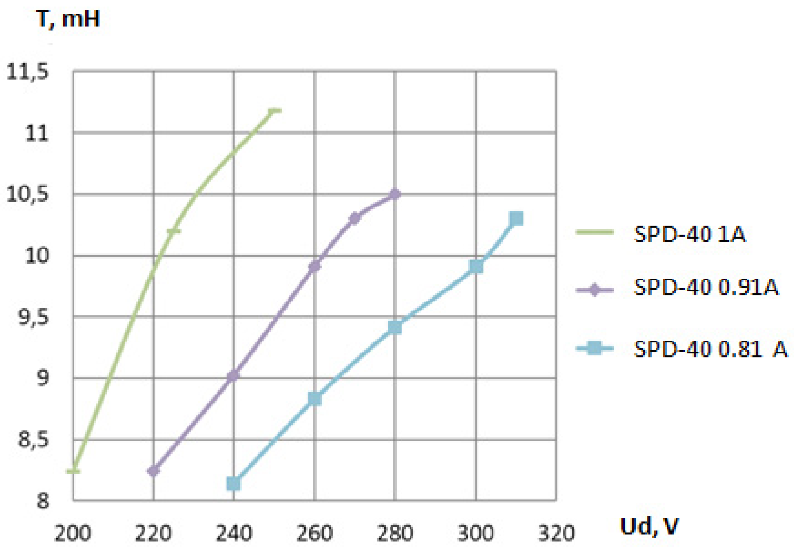

Figure 5. SPT-40 thrust dependence on discharge voltage while working on krypton

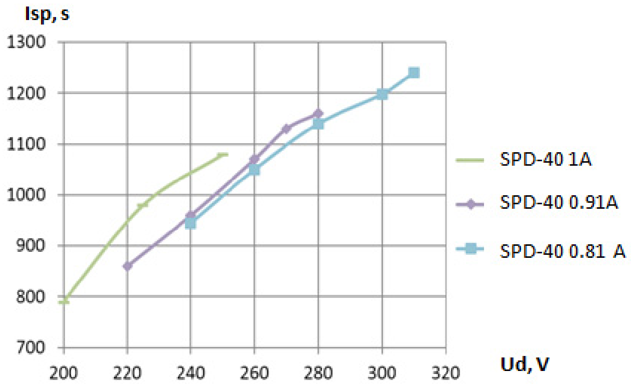

Figure 6. SPT-40 specific impulse dependence on discharge voltage while working on krypton

4.2. SPT-40 life tests

To clarify the question of how stable the parameters are on a long-run of operating time, a 150 hour duration test was carried out on the SPT-40 at nominal operating mode. During the first 18 hours of running time significant parameters fluctuation, within 150 s in case of specific impulse, and within 1 mN in case of thrust, were noted . These fluctuations could have been caused by aging of the primary thrusters after manufacturing or due to an unstable cathode operation. After the first 18 hours the cathode failed and was changed. After this change, the thruster was operating stably in the selected mode.

The thruster parameters become stabilized at 1150 s specific impulse and 9.9 mN thrust levels with thrust efficiency of 22.7 %. Then they gradually decreased to 1043 s, 9.42 mN and 19.4 %, respectively. There was also a flow rate increasing from 0.87 mg/sec to 0.92 mg/sec. At the same time with the drop in characteristics and efficiency, there was temperature increase on the thruster elements. The significant decrease of the thruster parameters can be explained by erosion of the discharge chamber exit walls due to the increase of the accelerating channel cross-section, which causes a reduction of the mass flow and plasma density in the accelerating channel, as well as the reduction of the atoms ionization probability and mass utilization efficiency.

During the life tests, parametrical tests were carried out both on xenon and krypton. They showed that the parameter drop on other modes are of the same character.

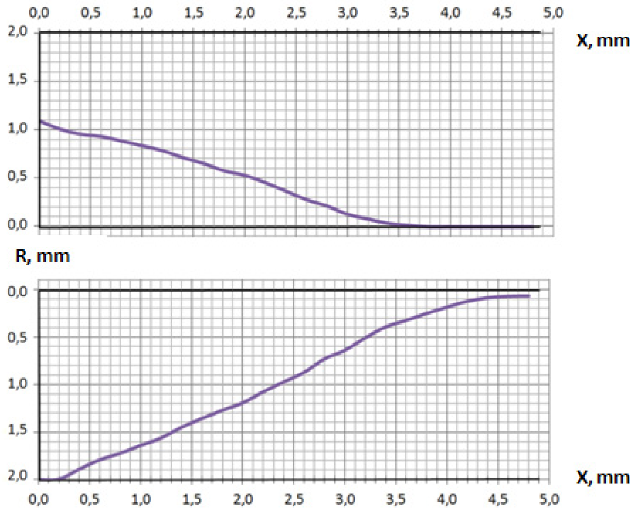

Figure 7. Wear line of the discharge chamber walls after 150 hours of operating time

Upon termination of the life tests, wear line measurements were made on the discharge chamber. Figure 7 shows the profiles of the discharge chamber inner and outer walls. Radial erosion of the outer wall is 1.1 mm, with width of erosion of 3.5 mm. Erosion of the inner wall reached the edge of discharge chamber and went deep into it for 0.3 mm, the width of erosion is 4.5 mm. This rate of wear can be explained by the warping of the accelerating layer at selected optimal mode: that is why thruster improvement should be focused on decreasing ion flow to the inner wall surface of the discharge chamber.

The carried out tests proved that the main way of increasing specific impulse is to increase the density of the propellant flow rate in the accelerator channel, and that it is possible to get full specific impulse not less than 1100 s working on krypton with the discharge power not more than 250 W. At the same time, tests showed the negative effects of model downsizing, these effects are:

- high wear rate of the inner wall of th discharge chamber. This rate prejudices the ability of thruster for a long service life at operating modes with a high specific impulse;
- great reduction of specific impulse during 150 hours of test firing;

Taking the above mentioned into account, the low power SPT model will be modified to shift the ionization and acceleration layer in the exit direction and to increase the discharge chamber wall thickness by optimization of the magnetic system.

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