Chapter

Hall Thruster Erosion

Andrey Vitalievich Loyan and Alona Nikolaevna Khaustova

Abstract

Hall thruster (HT) is one of the thrusters that are systematically applied in space. If to compare HT with plasma ion thrusters, it has lower lifetime and specific impulse. HT has a set of advantages, and that is why interest to this plasma thruster is high. It has relatively simple design and technology of production. HT does not require a complex power supply unit, and it is very important for spacecraft. Propulsion system on the base of HT has lower mass, simpler technology, and less time of production. One of the main HT characteristics that require improvement is the lifetime of thruster. As it is known, one of the main factors that decrease thruster lifetime is the wear of discharge chamber (DCh). With the analysis of demands to HT, it is understandable that the required lifetime is more than 10 years. So the question about lifetime of the HT is still open. This chapter presents the overview of the thruster elements lifetimes and the overview of methods of thruster erosion investigation. It shows advantages and disadvantages of optical methods of DCh erosion rate investigation. Chapter presents modified method of optical investigation. The results of HT research under various modes of operation and results of tests with different ceramic are presented.

Keywords: electric propulsion thruster, stationary plasma thruster, lifetime, discharge chamber, method diagnostics, optical emission spectroscopy, erosion rate

1. Introduction

With the increasing of number and complexity of tasks performed by modern spacecrafts, more high requirements appear for the propulsion unit (PU). Today, units based on hall thruster (HT) are one of a promising type of PU. Modern HT meets customer requirements by the following parameters: efficiency, specific impulse, and thrust price. However, the claimed thruster lifetime cannot fully meet the requirements of the technical task [1].

The common symptom of the completion of the HT's lifetime is the moment, when the elements of the magnetic system, the cathode, are bombarded by the ion flow first time, and this prose is followed by degradation of integral characteristics. To estimate the technical state of the discharge chamber (DCh) wear, the HT tests and measures of the erosion of the material are carried out [1, 2].

The problem of research of DCh wear is based on two factors. First, the maximum number of HT orders for a single customer does not exceed 10 units per year. To use the classical mathematical statistics, volumes of samples should count dozens of samples and tests should last hundreds thousands hours. To determine the HT lifetime, which is 4000 hours, it is necessary to provide tests of 130 thousand hours for 32 thrusters, which exceeds the cost of PU. The dissemination of the test results from individual samples to a whole range of thrusters, even with one design, is unreasonable because of the lack of statistical data and high requirements for space technology.

Second, while using the reduced lifetime tests, the duration of the experiment is about 10% of the physical thruster lifetime. For example, for HT with 4000 hours of operation time, a test with a minimum base of 400 hours is required. The cost of such tests can be compared to the cost of one HT.

These factors determine the necessity of searching for new diagnostic methods of DCh wear—to increase the HT lifetime and to reduce the test duration [1–3].

Performance of the mentioned works on increase in a resource of the HT can be done in several directions:

- search for new ceramic materials;
- improvement of thruster design;
- improvement of mathematical model of thruster in order to find new ways of enhancing sustainability of the DCh to high-energy ion flow; and
- search for new ways of HT resource increasing, for instance, by means of selection of its operation mode.

The search for new materials is a direction of work that requires not only significant material but also durable time expenses; positive result will undoubtedly lead to DCh recourse increase, but will not be able to influence on characteristics of finished thrusters.

The existing mathematical models of HT allow us to simulate the process of DCh insulator wear and based on the results of calculations, with reasonable accuracy, to predict the behavior of HT erosion. Despite this, leading HT developers are inclined to believe that trusted quantitative data can only be obtained experimentally on the basis of long-term resource tests.

The results of the analysis of the state of wear research of the DCh HT show that today there is no possibility to make a list of the main guaranteed recommendations according to which it would be possible to develop a design of the thruster with a lifetime up to two times higher than existing analogues; therefore, HT improvement works are carried out in all of the previously mentioned areas.

This chapter presents the results of research of the HT DCh edge wear at various operating modes (with different ratios of coil currents at stable values of the discharge voltage and mass flow rate).

The research results of low-power HT with different materials of ceramic insulators are presented.

2. Possible Hall thruster lifetime limiting elements

2.1 Main components and operating principle of the HT

HT is a plasma thruster in which thrust is created by propellant ions, formed and accelerated in a discharge in crossed electric and magnetic fields.

In the traditional version, HT consists of two main nodes—the cathode and anode blocks (**Figure 1**). The cathode (1) is performed according to the scheme of a hollow cathode, located on the side of the anode block and is a source of electrons. The purpose of the cathode is to ensure the thruster ignition, maintains its normal operation,

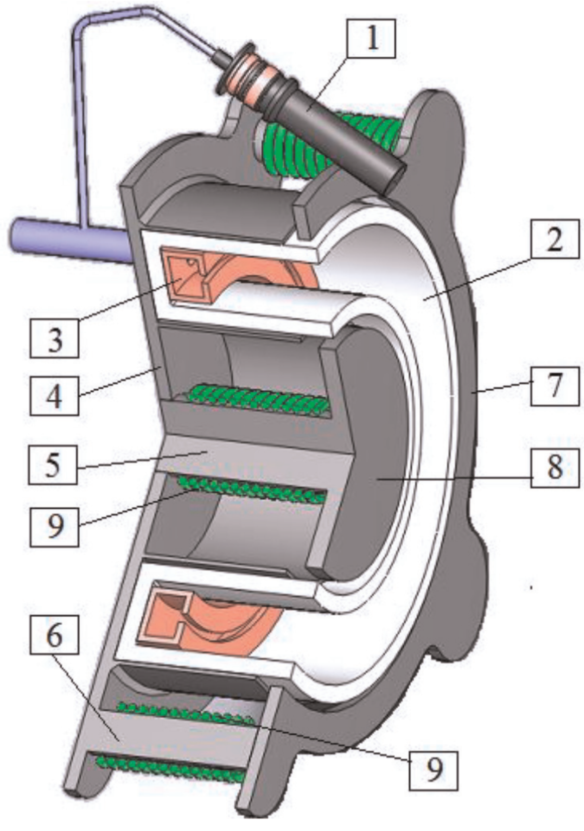

Figure 1.
Principle scheme of the HT: 1—cathode-neutralizer; 2—discharge chamber; 3—anode; 4—magnetic part; 5 and 6—inner and outer cores; 7 and 8—outer and inner poles; 9 and 10—inner and outer coils.

and also neutralizes the charge of the plume flowing out of the thruster. The anode block consists of a magnetic system and accelerating channel (2) with an anode (3). The magnetic system (MS) includes: magnetic part (4), inner core (5) and an outer core (6), an outer pole (7) and an internal pole (8), as well as a coils (9 and 10). The MS is constructed in such a way that a radial magnetic field is formed in the discharge channel (DCh) located in the gap between the magnetic poles. DCh is limited by coaxial cylindrical walls of dielectric material, in the base of which anode is located, which also performs the function of supplying gas to the thruster channel [4].

The thruster works as follows: the propellant through the anode comes via the DCh. Discharge voltage is applied between the cathode and the anode. Under the action of electric field, electrons begin to move from the cathode to the anode and enter the crossed electric and magnetic fields. The magnitude of the magnetic field induction in the DCh is chosen such that the Larmor radii of the electrons r_e and the ions r_i satisfy the condition $r_e \ll L \ll r_i$, where L is the length of the DCh.

Under these conditions, the electron motion is performed in the azimuthal direction, and in the direction of the anode, displacement occurs due to collisions with neutral and charged particles, with the walls of the DCh, and also because of the plasma oscillations.

During the operation of the thruster, the electrons moving to the anode ionize the atoms of the propellant, and the ions that are formed are accelerated along the electric field, creating a reactive thrust. At the thruster exit, the ion flow is neutralized by electron flow created by the cathode.

2.2 Discharge chamber lifetime

In the region of the DCh exit, an ion stream is produced, and some of which is directed not along the axis of the thruster, but on the wall of the DCh. In the plasma of the HT, the ion flux reaches an energy level of tens, hundreds, and thousands of electron volts. Upon impact against the surface, the ions begin to "dissipate" it, that is, knock out one or more atoms (physical sputtering—erosion), ions (emission), electrons (emission), or fragments of molecules (chemical sputtering). Bombarding ions can acquire electrons on the surface and be reflected from it in the form of neutral atoms, the neutralization process. Ions can be bound to the sample surface (adsorbed). The listed processes are accompanied by electromagnetic radiation from ultraviolet to X-ray ranges.

The ion energy greatly exceeds the covalent bond energy of the particles in the layer and the weak Van der Waals and electrostatic interaction between the layers, which leads to the appearance of various types of physical sputtering, which are divided into several types: primary direct knockout, sputtering by linear cascades, and thermal peaks [5].

In the first case, the ion transmits to atoms enough amount of energy, so that atoms are able to leave the material after a small number of collisions. In two other sputtering modes, the amount of transmitted energy is sufficient to excite the displacement from the equilibrium position of whole groups of atoms that overcome the surface energy barrier and leave the wall of the DCh. This can explain the occurrence of zones of normal and abnormal erosion on the surface of ceramic inserts.

The main mass of sputtering product of the DCh material is neutral atoms, and the fraction of ions does not exceed 1% [6]. Ionized erosion products are recorded only at high values of the discharge voltage; the number of emitted ions of the material is by 2–4 orders of magnitude less than the number of emitted atoms.

The result of the erosion process can be traced visually after the tests. **Figure 2** is the photo of new 0.1 kW power hall thruster that is developed by the Scientific-Technological Center of Space Power and Engines (STC SPE) of National Aerospace University named after N. Ye. Zhukovsky "Kharkiv Aviation Institute," Ukraine. **Figure 3** presents the ceramic wall of the HT 0.1 kW after 92 hours of operation. There are areas of normal and abnormal erosion.

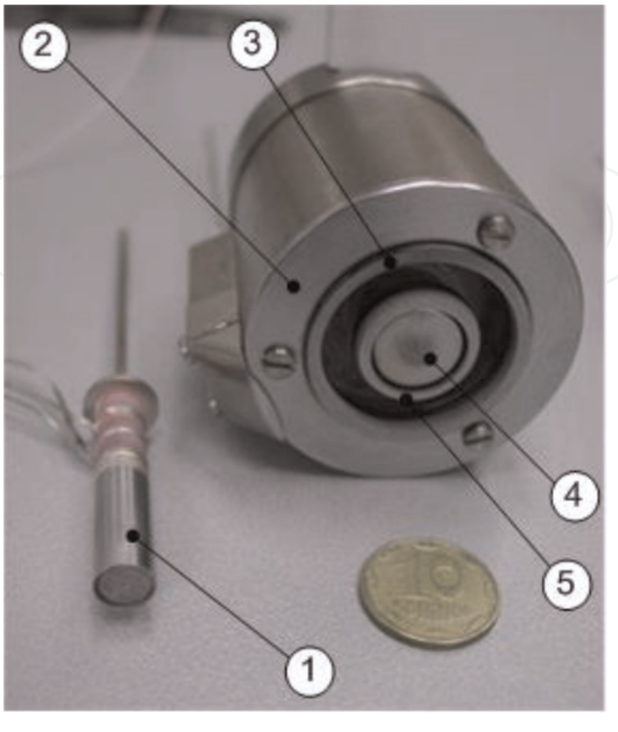

Figure 2.
Photo of the new hall thruster of 0.1 kW power and cathode: 1—cathode-neutralizer; 2—magnetic pole; 3—outer ceramic; 4–inner poles; 5–inner ceramic.

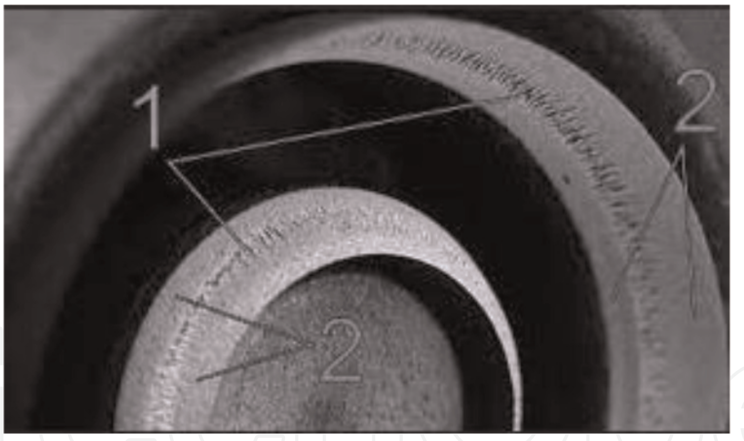

Figure 3.
Erosion belt of the thruster of 0.1 kW after 92 hours of operation: 1—abnormal erosion; 2—normal erosion.

The width of the erosion belt depends not only on the thruster design, the field distribution, but also on the DCh material and the choice of the thruster operation mode.

Resistance to the wear of the DCh wall material depends on more than 20 parameters, the most important of which are composition, density, porosity, and manufacturing technology [7].

2.3 The cathode lifetime (ignition electrode and emitter)

In spite of the fact that the cathode neutralizer is located in the zone with the minimal influence of the ion flow (i.e., outside the thruster plume), the fraction of ions with high-energy values is present in the near-cathode region. This leads to a gradual sputtering of the cathode block (**Figure 4**).

The most closely located to the DCh section element of the cathode is the ignition electrode (IE) (**Figure 6**). The goal of IE is to create an initial discharge between the emitter and the IE. Next, the main discharge is ignited between the anode and cathode blocks.

Analysis of the results of long-term lifetime tests carried out in the EDB Fakel Kaliningrad [9] showed that the volume of IE material sputtering is linear until the

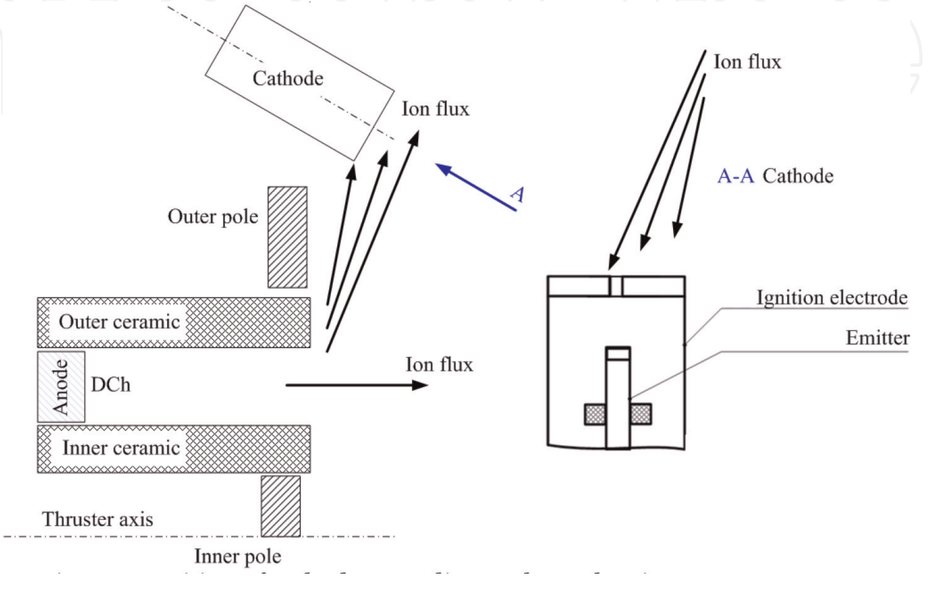

Figure 4.
Position of cathode according to the DCh exit.

length of the outer insulator exceeds the length of the outer pole tip. As the length of the outer ceramic insert decreases, the insulator ceases to be a barrier between the plasma plume and the cathode block, and thereby opens both the pole tip and the cathode for ion flow influence. The results of long tests of about 3000 hours or more showed that even with full wear of the end part of the IE, it fully performs the function of starting the thruster. According to the forecast, the IE lifetime is more than 10,000 h.

The cathode emitter lifetime is determined by the rate of material loss of its emission part. The statistical data show that during the time of the cathode block lifetime tests with duration of more than 8000 hours, the emitter volume loss is less than 8%. The predicted emitter lifetime is not less than 15,000 hours [15].

2.4 Hall thruster magnetic system lifetime

HT magnetic system materials possess low sputtering coefficients as compared to ceramic insulators of DCh. The design of discharge chamber exit of the thruster is designed in such a way that the edges of both the outer ceramic insert and the inner ceramic insert block the ion flow to the magnetic poles.

Obviously, despite the applied constructional solutions, there is a weak flux of high-energy ions in this region. However, the material mass leakage is negligible. The results of experiments on the determination of the initial stage of materials of the magnetic system wear at different thicknesses of the walls of the DCh show that with a proper selection of the geometry of the DCh walls, a lifetime of a magnetic system of more than 15,000 hours can be achieved for a 1.35 kW HT model [8].

The results of long-term HT lifetime tests show that at first, DCh edges are susceptible to ion bombardment discharged, and only after the total sputtering of the edges of the insulators, magnetic system elements and cathode block are beginning to significantly erode. Hence, one of the most critical elements of HT from the point of view of the lifetime is the edge of the DCh insulators.

3. Overview of methods of Hall thruster erosion measurements

A number of direct and indirect methods have been developed to study the rate of erosion of the HT DCh, each of which has unique methodological differences.

3.1 Direct methods

During the thruster operation, the profile of the edges gradually changes due to the loss of the weight of the DCh insulators. If the design of the thruster allows rapid extraction of ceramic inserts from the HT anodic block quickly and without causing defects, then the mass change control (weighting methods) is carried out, for example, using laboratory scales (WA-21).

For the initial masses of outer and inner ceramics m_{OC_0} and m_{IC_0}, the mass of the insulator is taken just after its manufacturing. Further tests are carried out with the HT unchanged operating mode. The time base of the experiment is divided into several stages, for example, 10–50 hours each, depending on the thruster power and the rate of erosion. After the end of each stage of the tests, the insulators are removed from the anode block, and their mass, mn1 and mv1, are measured. Mass loss rate, mg/h, of the sample is determined by calculating the difference between the initial and measured masses and dividing it into a time test base [9].

In order to control the radial erosion, mm/h, measuring instrumental microscopes are used.

Using direct methods, data on the rate of erosion of ceramic units of measurement—mm/h or mg/h are received. The error in determining the wear depends on the stability of the thruster operation and the accuracy of the measuring equipment. There is no need for a sophisticated calculation method.

3.2 Indirect methods

In order to be able to monitor the erosion rate directly during thruster operation, there are a number of indirect measurement methods. These include optical methods and special methods [10].

3.2.1 Method of quartz crystal

The principle of the method is to trap the sputtering products of ceramic insulators on a quartz crystal (**Figure 5**).

The design of the recording device is designed in such a way that the ionic component of the plume would not be able to overcome the potential barrier created by the electric field applied to the housing. Permanent magnets are used to trap electron component of the flow. Magnets characteristics are selected depending on the thruster plume. The quartz crystal is attached to the resonating circuit. During the experiment, the frequency of the loop oscillation is monitored, which changes when the film forms on the surface of the crystal from the deposited neutral atoms—the erosion products of the thruster material.

Analysis of the data obtained using this method showed good alignment of results and the method of optical emission spectroscopy (OES).

3.2.2 Laser-induced fluorescence

Laser-induced fluorescence (LIF) has also been used for several decades to study the fluorescence spectra of HT plasma [9].

LIF is considered a highly sensitive method [8], since the excitation rate is independent of the plasma parameters, with stable operation of the thruster, and there is a possibility to adjust the equipment to obtain maximum sensitivity for each

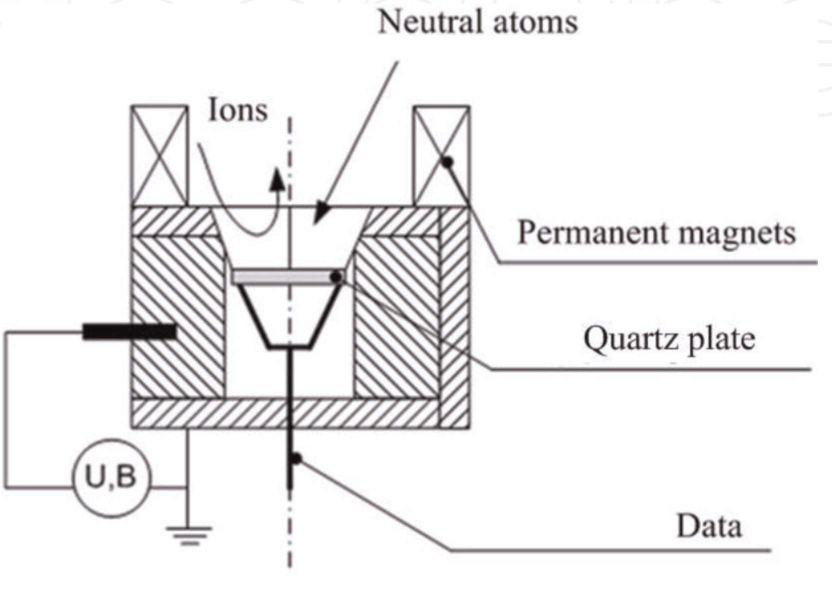

Figure 5.
The device for recording the mass loss of the DCh insulators by the quartz crystal method.

component under study. However, the need to install and set a large number of measuring equipment, the need to reconfigure the laser to investigate various components of the spectrum, critically limits the scope of the method [9].

3.2.3 Mass spectrometry

One of the methods for recording HT sputtering products is the mass spectrometry method [8]. Modern mass spectrometers have high resolution and can be used with all kinds of particles in different states of excitation and different concentrations of the sample under study.

Despite the significant advantages of modern mass spectrometers, high sensitivity, in comparison with other optical methods, unambiguous identification of particles, and a large operating range of masses, they have a number of disadvantages. First, mass spectrometers are complex instruments both in operation and in maintenance. Second, modern mass spectrometers are an extremely expensive type of equipment, the cost of which is comparable to the cost of manufacturing several HTs.

3.2.4 Optical emission spectroscopy

The principle of the method of optical emission spectroscopy consists in recording the emission spectrum of the thruster sputtering products and recalculating the intensities of the spectral lines in the erosion rate [9]. Advantages of the method, namely contactless, relatively simple procedure for processing experimental data, and relatively simple technical organization of measuring equipment, led to the extensive use of OES as one of the main diagnostic tools in the field of research of the technical state of HT.

The requirements to the method of HT insulators edges erosion rate are next:

- non-intrusive, estimation of erosion without any contact with thruster itself or plasma plume;
- technically simple;
- short-term preparation time of measuring equipment;
- no need for multiple calibration and adjustment of measuring equipment;
- possibility of multiple use of recording sensors;
- the ability to do measurements during the thruster operation;
- short-term procedure of experimental data processing;
- measurement of the external and internal insulators erosion rate separately.

Methodological requirements are as follows: relatively high measurement accuracy and unambiguous interpretation of the results.

The analysis of the methods for diagnosing the rate of erosion of the spraying products of the edge edges of HT insulators showed that in order to obtain qualitative measurement results, two diagnostic methods should be used throughout the thruster test cycle: OES and measurements by direct methods.

4. Detailed description of the optical emission spectroscopy (OES) method. OES development: method of the optical emission spectroscopy with the scanning of thruster plasma through collimator (OESSC)

4.1 Basic scheme and principle of measurements with the OES method

The basic scheme of the OES method is shown in **Figure 6**. Radiation of the plasma of the thruster through the inspection flange and the lens by means of an optical cable is transferred to a spectrometer where the spectrum is decomposed. Further, the signal is transmitted to the computer and output as a dependence of the intensity of the spectral line on the wavelength. As a rule, the inspection flange of a vacuum chamber is made of quartz glass of KU-1 type with a low absorption coefficient of radiation in a wide range of wavelengths.

It is obvious from **Figure 8** that when using the basic scheme of the OES method, it is not possible to register radiation separately from each edge of the DCh ceramic.

4.2 Basic scheme and principle of measurements with the OESSC method

For the spectral measurements from small regions of the plasma radiation of the thruster, the OES method experimental scheme was modified. From the OES measurement scheme, the collecting lens was removed, and the optical cable was installed into the vacuum chamber at the minimum possible distance from the DCh cut. A collimator was installed on the fiber optic cable (**Figure 7**). Collimator is a device that geometrically reduces the divergence angle of the optical fiber. For a standard optical cable, the divergence angle is equal to 25.4°. For the developed optical receiver, which consists of a collimator and a cable, the divergence angle was 4.5°.

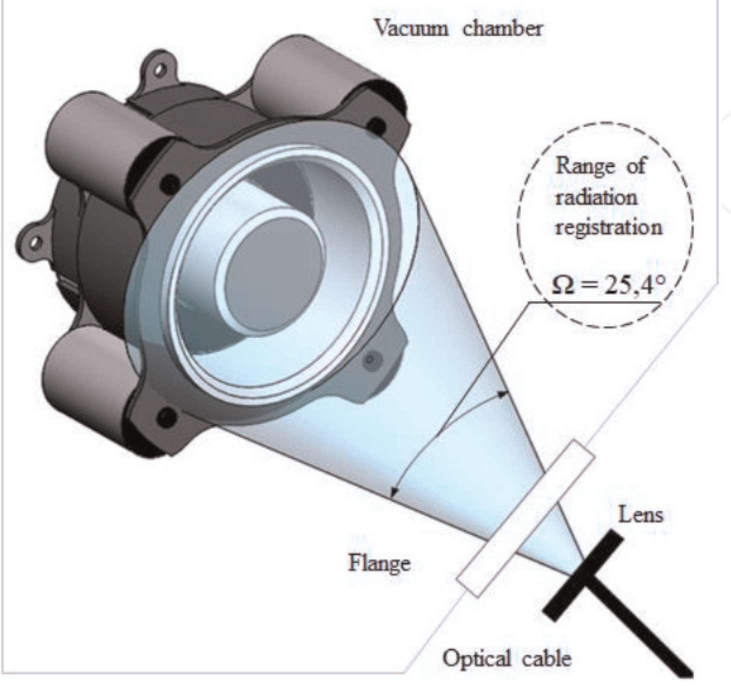

Figure 6.
The scheme of measurements of the rate of erosion by the OES method.

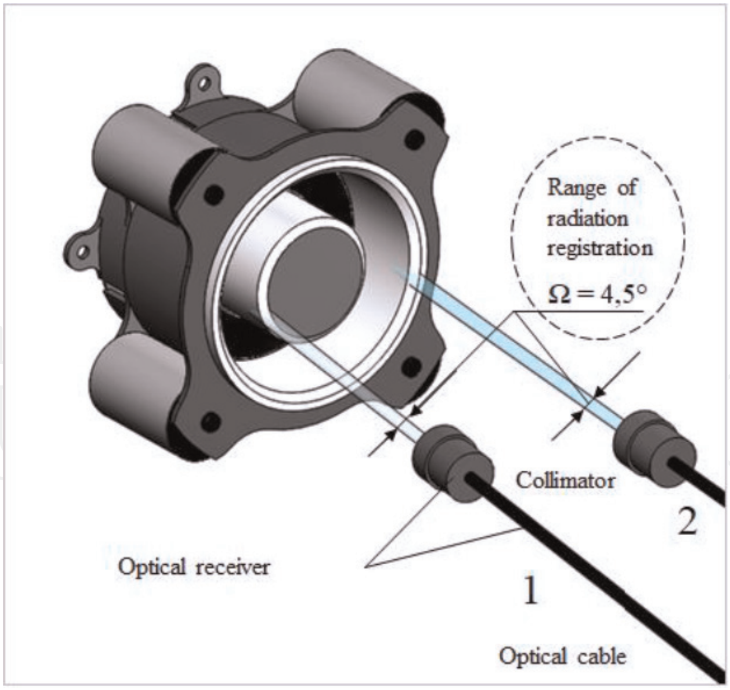

Figure 7.
Scheme of measurements of the erosion rate by the OESSC method: 1—position of measurements of "inner ceramic"; and 2—position of measurements of "inner ceramic" and "outer ceramic."

It is also possible to scan radiation from different regions of the DCh by installing a registration element on a coordinate platform. According to the presented scheme, the improved method of OES was called the method of optical emission spectroscopy with scanning of the plasma radiation of the thruster through a collimator (OESSC).

The above scheme of measurements by the OESSC method has a number of advantages:

- the possibility to obtain data on the wear rate of insulators from each of the ceramic inserts separately during the tests of the thruster;
- the ability to carry out measurements of the entrainment of the material separately of different parts of the thruster magnetic system during the tests;
- possibility to register the degree of wear of ceramics in the azimuth direction;
- nonintrusive—no contact of measuring equipment with thruster plasma, which may lead to change thruster operation mode and the change of the plasma parameters;
- a simple procedure of experimental data processing;
- absence of complicated procedures for calibration and adjustment of measuring equipment; and
- the possibility to get erosion data at different thruster operating modes, namely at different voltages, mass flow rates, and coil currents [11].

One of the method disadvantages is the installation of a sensitive optical cable in a vacuum chamber, which leads to the dusting of the fiber with the products of thruster erosion. However, this problem was solved by installing of the quartz glass protective screens to the sensitive element of the optical fiber [12].

4.3 Processing of the spectral measurement results

The results of spectral measurements of two thrusters with different materials of ceramic insulators BN and BN + SiO_2 are presented in **Figure 8**. As can be seen in the UV-range, boron lines with a wavelength of 249.66 and 249.77 nm are presented on the spectra of both thrusters. These boron lines that are suitable for qualitative analysis are well recorded. Silicon lines are presented on the thruster with BN + SiO_2 ceramic and absent on the thruster with BN ceramic. The intensities of silicon line in UV-range are relatively high, so these lines can be used for the quantitative analysis.

Known method of erosion rate computation based on the thruster DCh radiation spectrum measurements has a comparable character. It means that, for example, computational data can give assessment of erosion rate differ at different thruster operational modes or how the erosion rate changes in time. OES equation does not describe how the optical fiber position and DCh erosion area influence the registered emission flow. These data are necessary for the computation of erosion rate from different DCh walls.

That is why for the OESSC method, next calculation expression is used

$$Er = I^{B}_{249.77} \frac{{R_B}^2}{V_B} \frac{I^{Xe}_{828.01}}{I^{Xe+m}_{484.43}} \tag{1}$$

where Er is the erosion rate of the material; $I^{B}{}_{249.77}$ is the lighting of the optical cable by the boron atoms on the wavelength 249.77 nm; $I^{Xe+m}{}_{484.43}$ is the lighting of the optical cable by the xenon metastable ions on the wavelength 484.43 nm; $I^{Xe}{}_{828.01}$ is the lighting of the optical cable by the xenon atoms on the wavelength 828.01 nm; R_B is the distance from the source to the radiation detector, m.; and V_B is the amount of radiation from DCh wear products, m^3.

This expression is used for defining the erosion rate from different parts of the DCh.

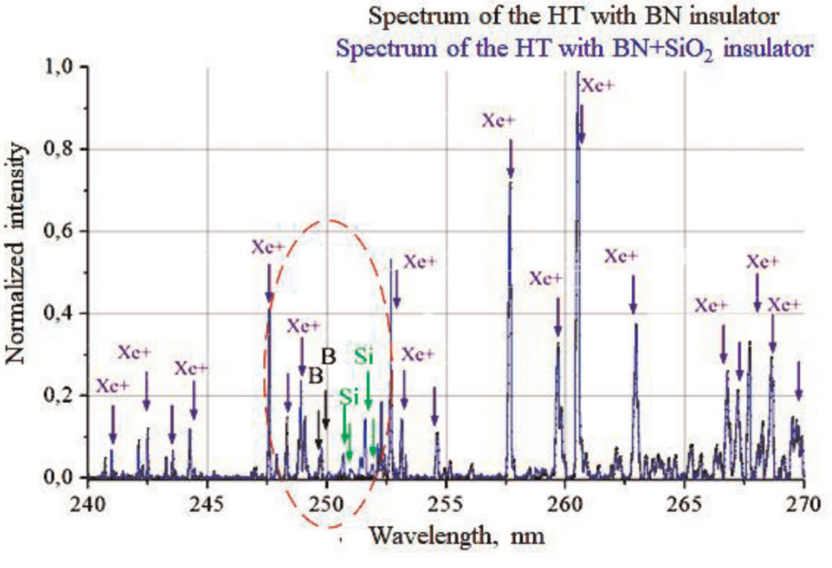

Figure 8.
Spectrum in the UV-range 240–270 nm: black—HT with BN insulator; blue—HT with BN + SiO_2 insulator.

5. OES studies of plasma propulsion systems of 100 W power

5.1 OES test equipment and its adjustment

For the purpose of preliminary studies on the influence of the modes of operation of the HT on its erosion characteristics for measuring the spectra of optical radiation of the plasma plume of the 0.1 kW HT, an experimental installation was established, and the scheme of which is shown in **Figure 9**. The radiation emitted by the plasma (1) 0.1 kW HT, through a quartz window (2) (diameter—40 mm and thickness—5 mm), was observed with the help of a device for measuring the spectrum located outside the camera. The angle of observation of the plasma plume at the cut of the thruster was 60° relative to the chamber axis. With 10 cm of focusing lens (3), the radiation is collected and focused on a light conductive fiber (4) with a diameter of 1 mm. The distance between the plasma plume and the lens was about 80 cm. The end of the fiber is connected by a special adapter with the inlet of the spectrometer (5). A lens with a focal length of 10 cm gave an approximately 9× magnification. With an optical fiber with a diameter of 1 mm, the spatial resolution was about 9 mm in diameter. Thus, the installation captured most of the plasma jet in the thruster channel and its exit.

The end of the optical cable through a special adapter connects to the input port of the spectrometer USB2000. This mini spectrometer, manufactured by Ocean Optics (USA), was kindly provided by Laboratoire de Physique des Gaz et des Plasmas [13]. It was used to cover the considered range with a resolution that is sufficient to distinguish optical lines. Moreover, its weight (600 g), dimensions (15 × 11 × 5 cm), and power consumption (100 mA) make it an excellent candidate for the use in summer experiments to study the erosion of ceramics and the optical spectrum of the plasma plume of the thruster (**Figure 9**).

The light entering the spectrometer is refracted by a fixed dispersing prism and is directed to the charge coupled device (CCD) line with 2048 elements. So, in one shot, this spectrometer gives a spectrum of wavelengths of 380–830 nm with a resolution of 0.2–0.22 nm. The spectrometer is connected to the laptop through the USB interface. The computer controls the parameters of the spectrometer USB2000

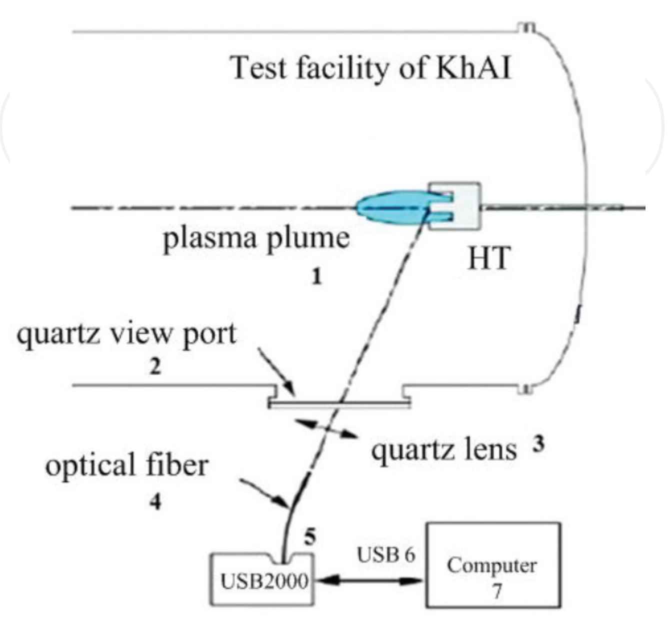

Figure 9.
Experimental equipment: HT—Hall thruster; 1—plasma plume; 2—quartz view port; 3—quartz lens; 4—optical fiber; 5—spectrometer USB-2000; 6—USB connection cable; and 7—computer.

through the computer, and the graphical interface allows you to get a spectral image that can be saved as a text file with data.

Such a measuring spectrometric system is quite user-friendly, promptly provides information about the controlled spectrum, and thanks to a numerical representation, which allows us to conveniently store information and compare it with another that was previously registered.

5.2 OES studies of the HT erosion at different operation modes

Together with the Laboratoire de Physique des Gaz et des Plasmas, Université Paris, Laboratoire d'Analyse Spectroscopique et d'Energétique des Plasmas, Université d'Orléans, and Laboratoire d'Aérothermique, the 0.1 W HT optical (spectral) tests were conducted to determine the effect of the regime of the thruster on its erosion characteristics [13]. Measurements were provided on the test facility as shown in **Figure 10**. Experimental parameters, discharge voltage (Ud) from 200 to 300 V in a step of 20 V, and also the current on the solenoid of the magnetic system of the thruster varied in the range of 1.5–3.0 A. All measurements were made at two values of xenon consumption: 0.20 and 0.25 mg/s.

In calculating of this parameter, the power of the solenoid was taken into account, but was neglected by the mass flow of xenon through the cathode. The maximum value of the efficiency (0.353) of HT during this experiment was obtained at a discharge voltage of 300 V and a mass flow of xenon 0.25 mg/s.

Xe I (828.01 nm), Xe II (484.43 nm), and Al I (396.152 nm) lines were distinguished for the analysis of the level of erosion of the stationary plasma thruster with ceramics from the ABN. These three lines made it possible to analyze the rate of erosion. This analysis was conducted with Laboratoire d'Analyze Spectroscopique et d'Energétique des Plasmas, Université d'Orléans, and its results are published in the materials of the international conference [14].

The Xe II xenon ion emission occurs due to the transition from the wavelength of 484.43 nm from the initial level $5p^4\left(D^0_{7/2}\right)6s - 5p^5\left({}^2P^0_{3/2}\right)6p$ of 14.10 eV (80118.962 cm^{-1}) to the level 11.54 eV (68045.156 cm^{-1}). The upper level $5p^4\left(D^0_{7/2}\right)6s$ is basically two metastable states Xe^+ $5d^4D_{7/2}$ and $5d^4F_{7/2}$.

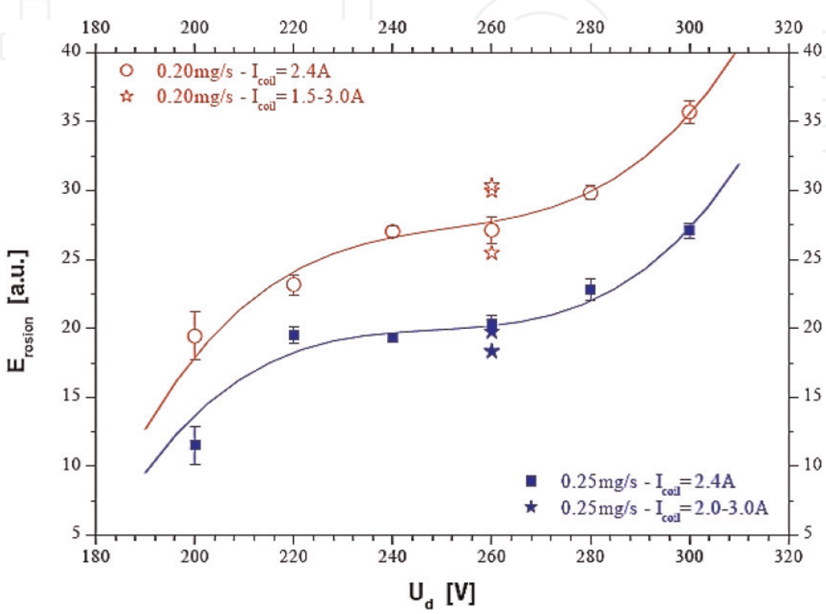

Figure 10.
Dependence of the erosion from the discharge voltage.

The two lines for aluminum are close to the transition $3s^2 3p - 3s^2 4s$ to the emission level of 3.14 eV (25347.756 cm^{-1}): the first one is 394.40 nm and the other one is 396.15 nm. Second quasi-resonance line is used. This line Al I has an amplitude of light oscillations and is located near the lines Xe II. The spectrometer should be able to isolate this line from the set of other lines of Xenon plasma emission. To determine the exact value of the AlI line 396.15 nm, a numerical method of data approximation was used for Gauss's multi-profile profile. The radiation level is also occupied by electrons excited from their ground state $\left(2P^0_{1/2}\right)$ [15].

The erosion of the thruster ceramics was determined from the ratio of the intensity of the lines

$$E_{rosion} = \frac{I(Al\,I, 396\,nm)\cdot I(Xe\,I, 828\,nm)}{I(Xe\,II, 484\,nm)}. \quad (2)$$

where intensities were determined as:

$$I_{Al}(396\,nm) \propto n_{Al}\cdot n_e \cdot k_e^{Al},\ I_{Xe}(828\,nm) \propto n_{Xe}\cdot n_e\cdot k_e^{Xe},\ I_{Xe^{+m}}(484\,nm) \propto n_{Xe^{+m}}\cdot n_e\cdot k_e^{Xe^{+m}} \quad (3)$$

where n_{Al}, n_{Xe}, $n_{Xe^{+m}}$—metastable aluminum densities, neutral and ionized xenon, respectively, and k_e^{Al}, k_e^{Xe}, $k_e^{Xe^{+m}}$—electronic excitation coefficient for the corresponding upper state. The ratio of the intensity of the lines is used to determine the concentration of aluminum.

$$E_{rosion} = \frac{I(Al\,I, 396\,nm)\cdot I(Xe\,I, 828\,nm)}{I(Xe\,II, 484\,nm)} \propto \frac{n_{Al}\cdot n_e\cdot k_e^{Al}\cdot n_{Xe}\cdot n_e\cdot k_e^{Xe}}{n_{Xe^{+m}}\cdot n_e\cdot k_e^{Xe^{+m}}}. \quad (4)$$

Applying an actinometric hypothesis, we obtain that the density of ionic metastable is proportional to the concentration of ions, reducing the value k_e^{Al} and $k_e^{Xe^{+m}}$ because of the equivalence of energy change (several eV), and this equation takes the form:

$$E_{rosion} \propto \frac{n_{Al}\cdot n_e\cdot k_e^{Al}\cdot n_{Xe}\cdot n_e\cdot k_e^{Xe}}{n_{Xe^{+m}}\cdot n_e^2\cdot k^{Xe+}\cdot k_e^{Xe^{+m}}} \propto n_{Al}. \quad (5)$$

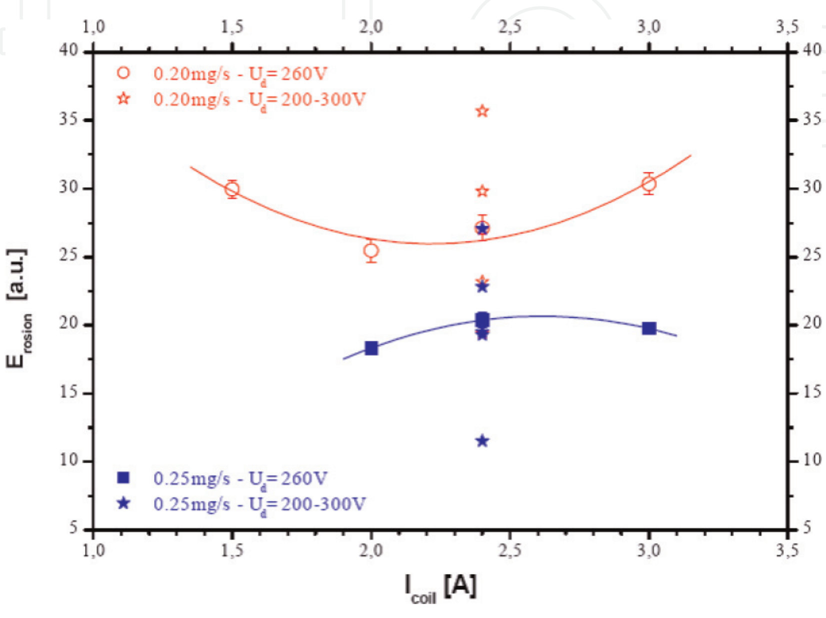

Figure 11.
Dependence of the erosion from the coil current.

To understand the behavior of the erosion in the regimes of thruster that were not measured, the experimental data were approximated by the polynomial dependence (**Figures 10** and **11**).

Figure 11 shows the dependence of the erosion on the coil current for a constant discharge voltage of 260 V and for two xenon mass flow (0.20 and 0.25 mg/s).

6. Experiment investigation of HT erosion with the OESSC and method of radial erosion measurements

As it was told, before OESSC method was developed to provide measurements of the HT erosion of outer and inner ceramics separately during thruster test was not possible for OES method. In this section, the results of the experimental investigation of two erosion measurements methods are presented: direct measurements radial erosion and OESSC method.

6.1 The algorithm of the OESSC method

In the Scientific-Technological Center of Space Power and Engines (STC SPE) of National Aerospace University named after N. Ye. Zhukovsky "Kharkiv Aviation Institute," Ukraine, 1.35 kW thruster was tested to determine the dependence of the DCh edges erosion parameters from the ratio of the magnetic system coil currents. The thruster was tested with a ceramic BN.

Algorithm of the diagnostics by OESSC method consists of several steps.

1. Maintenance of the experimental equipment (**Figure 12**).

Measuring equipment of the OESSC method consists of a block of high-resolution spectrometers for recording the radiation of HT in the range with the wavelength of 240–830 nm and two-coordinate platform for moving the optical receiver and the unit for protecting the optical fiber from dust.

2. Launch of the thruster and stabilization of the erosion parameters.

3. Measurement of the radiation spectra for each of the insulators and calculation of the erosion rate from the formula (6).

4. Repeat the procedure of spectrum measurements for each of the DCh ceramic inserts at different ratios of the thruster coil currents.

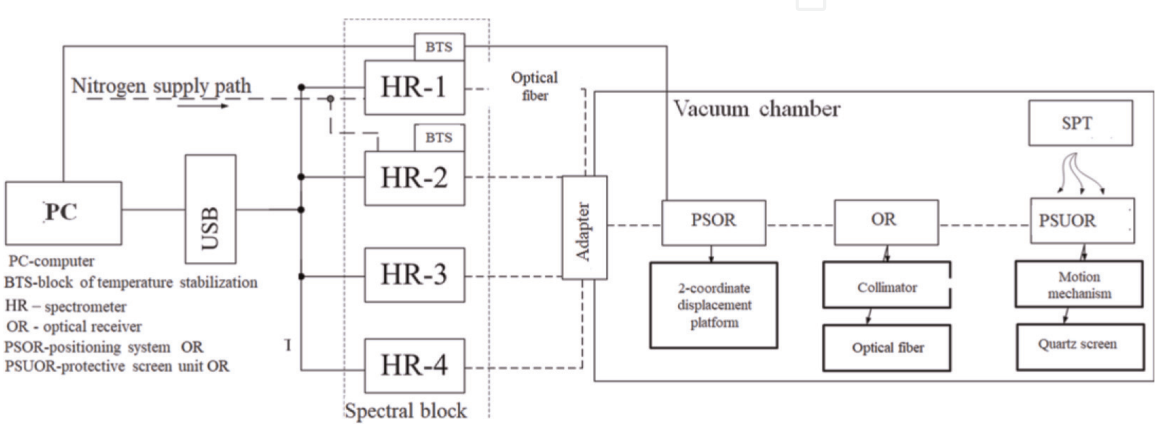

Figure 12.
Measuring equipment of the OESSC method.

5. Comparison of the erosion rate of insulators in different modes of HT.

The ratio of the erosion rates of edges obtained by the OESSC method (ΔEr) was determined like:

$$\Delta Er = \frac{Er_{\text{inner}\_ceramic} - Er_{\text{outer}\_ceramic}}{Er_{\text{inner}\_ceramic}} \cdot 100\% \quad (\text{if} Er_{\text{inner}\_ceramic} > Er_{\text{outer}\_ceramic}) or$$
$$\Delta Er = \frac{Er_{\text{outer}\_ceramic} - Er_{\text{inner}\_ceramic}}{Er_{\text{outer}\_ceramic}} \cdot 100\% (\text{if} Er_{\text{outer}\_ceramic} > Er_{\text{inner}\_ceramic}) \tag{6}$$

6. Development of recommendations regarding the optimal operating mode with the maximum lifetime of the thruster DCh edges.

6.2 The method of the radial erosion measurements

After taking measurements by the OESSC method and selecting the operating mode, the thruster is tested on a time base of 50 hours, and measurements of radial erosion by a direct method are performed (**Figure 13** and **Table 1**). As a basis for measuring the insulator edge thickness, the outer diameter of the outer insulator and the inner diameter of the inner insulator were chosen.

Measurements are provided with the help of an instrumental measuring microscope with an error of less than 0.0005 mm. To eliminate errors in the installation of the DCh relative to the microscope, each measured position is photographed.

Radial erosion is defined as the difference between the coordinates of the edges of the insulators before and after the thruster operation.

$$E_{RAD\_\text{OUT}} = e_{OUT\_INITIAL} - e_{OUT\_\text{FINAL}}$$
$$E_{RAD\_\text{IN}} = e_{IN\_INITIAL} - e_{IN\_\text{FINAL}} \tag{7}$$

where E_{RAD_OUT} and E_{RAD_IN} are changes in thickness of the edges of the external and internal insulators after the thruster tests, mm.

The radial erosion rate is defined as:

$$V_{RAD\_\text{OUT}} = \frac{E_{RAD\_\text{OUT}}}{t_N}, \quad V_{RAD\_\text{IN}} = \frac{E_{RAD\_\text{IN}}}{t_N}, \tag{8}$$

where V_{RAD_OUT} and V_{RAD_IN}—radial erosion rate of outer and inner insulators, mm/h; t_N—duration of the thruster test phase, h; and N—thruster test stage number.

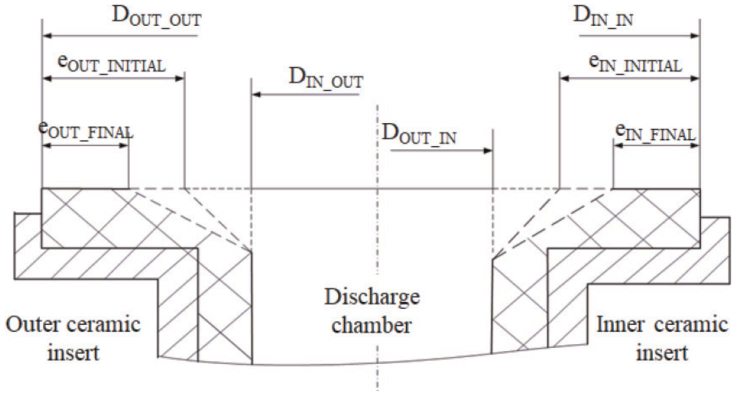

Figure 13.
Scheme of radial erosion measurements.

D_{IN_OUT}	Inner diameter of outer ceramic
D_{OUT_OUT}	Outer diameter of outer ceramic
D_{OUT_IN}	Outer diameter of inner ceramic
D_{IN_IN}	Inner diameter of inner ceramic
$e_{OUT\_INITIAL}$	Thickness of outer ceramic before the experiment
e_{OUT_FINAL}	Thickness of outer ceramic after the experiment
$e_{IN\_INITIAL}$	Thickness of inner ceramic before the experiment
e_{IN_FINAL}	Thickness of inner ceramic after the experiment

Table 1.
*Symbol definitions of **Figure 14**.*

Comparison of erosion rates of external and internal insulators was carried out by the following expression:

$$\Delta V_R = \frac{V_{RAD\_\max} - V_{RAD\_\min}}{V_{RAD\_\max}} \cdot 100\%, \tag{9}$$

where V_{RAD_max}—erosion of the insulator for which the wear is greater, mm/h; V_{RAD_min}—erosion of the insulator for which the wear is lower, mm/h.

Results of the erosion measurements with direct methods are presented in **Table 2**.

Thruster operation modes: I—mode with the lowest discharge current, current of inner coil—5 A, and current of outer coil—5 A.

As it is easy to see from the results on the mode with the lowest discharge current, erosion of ceramic walls is not uniform.

6.3 Comparison of results accepted by the OESSC method and direct radial erosion measurements

Figure 14 shows the results of the erosion rate measurements by the OESSC method. It was found that in the operating mode of the thruster with the minimum discharge current (mode I), the difference in the erosion rate of insulators was about 32%, which corresponded to the data obtained with direct measurements. After diagnostics and comparing the irregularity of erosion in 25 regimes, it was found that at the operating mode II, the difference in the erosion rate of the edges does not exceed 0.3%. The results were confirmed in subsequent tests and measurements by a direct method. The time spent on the study of the thruster DCh wear by the OESSC method on 25 operating modes, taking into account the expectation of the time for stabilizing the erosion rate, was 7 hours, which made it possible to reduce significantly the search for optimal current of the coils of the magnetic system from the point of view of uniform wear of the edges of the insulators (**Figure 14**).

# Thruster operation mode	**I**
Ratio of erosion rates of insulators	ΔV_R, %
Direct method	33

Table 2.
Experimental results with the direct methods.

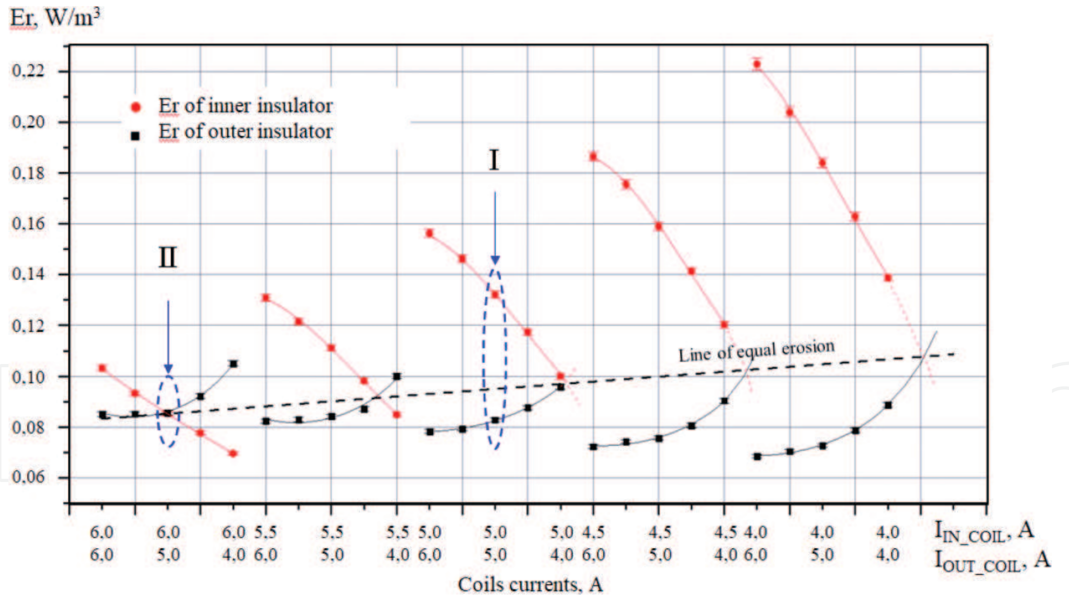

Figure 14.
Dependence of the erosion rate from the magnetic system coil currents.

# Thruster operation mode	I	II
Ratio of erosion rates of insulators	ΔV_R, %	ΔV_R, %
Direct method	33	0.249
OESSC method	32	0.243

Table 3.
Experimental results of erosion measurement with the OESSC method and direct method on two thruster regimes.

The erosion rate data for each of the insulators were approximated and extrapolated, in order to find regimes with the same erosion of the insulator edges. It is obtained that in the investigated range of coil current variation, there are five modes, under which the wear of the DCh edges will be uniform. However, the general wear of the material in other modes is greater. Therefore, mode II was selected for thruster operation.

After getting the results with the OESSC method, the experiment with direct measurements was provided for the thruster regime II. **Table 3** presents the results.

As it is seen from **Table 3**, results accepted by direct measurement were totally confirmed with the results of OESSC method measurements.

Conclusion was done to operate the thruster on the regime II, because on this regime, thruster lifetime is significantly higher.

7. Results of the investigation of several types of ceramic for the Hall thruster

Resource tests of the hollow thruster of power 100 W with one coil were conducted in the STC SPE of National Aerospace University named after N. Ye. Zhukovsky "Kharkiv Aviation Institute," Ukraine. The test purpose was to study the rate of ceramic insert erosion of BN with a different percentage of SiO_2 impurities.

To carry out the experiment, a thruster design was developed that allowed the rapid extraction of the outer and inner ceramic insulators without causing mechanical damage to their surfaces. The design of the thruster allows ensuring unambiguous installation of ceramic inserts in the DCh.

For each of the ceramic samples, the test time was 68 hours. The whole period of time was divided into four stages of 17 hours each. At the end of each stage of the test, the measured mass for each of the ceramic inserts was suspended and measured using a laboratory scale WA-21.

7.1 Ceramic insulator mass measuring method

The measurements of the ceramic mass are carried out as follows:

1. insulator weighing;

2. degassing of insulators in a vacuum oven at a temperature of 200° C for 30 minutes; and

3. reweighing of the samples till the original weight value was restored to 95%

It was found that the samples with the composition of pure BN, as well as with 5 and 10% impurities of SiO_2 reduced in mass for half an hour when they were in the atmosphere. It took more than 2 hours to restore the original mass of the remaining samples (20, 35, and 50% SiO_2).

The results obtained were used to measure the weight of the esterified substance at the end of each test stage. After stopping the tests, the thruster should be cooled. The temperature of the thruster was controlled by the voltage on the coil. Then the thruster was reinstalled from the chamber, was sorted out, and the ceramic insulators were mounted on the scales. Measurement of the insulator mass was carried out for 40 minutes. Counting of time began from the moment of air intake into the vacuum chamber.

Figure 15 shows the results of the experiment.

As you can see from **Figure 15**, the lowest erosion parameters have pure nitride boron ceramic.

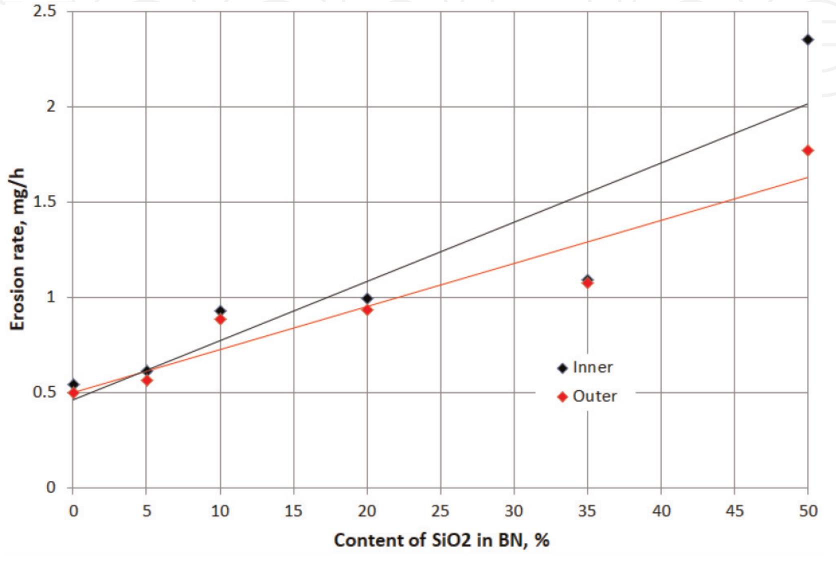

Figure 15.
The result of the tests: black—inner ceramic erosion rate; red—outer ceramic erosion rate.

8. Conclusions

One of the main HT characteristics that requires improvement is the lifetime of thruster. As it is known, one of the main factors that decreases thruster lifetime is the wear of DCh.

This chapter contains the results or investigation of thruster DCh erosion rate with the OES method. The algorithm of experiment is presented. The description of experimental equipment and its calibration process is presented.

Analysis of different intrusive and nonintrusive methods showed that there is no method that can give data about erosion rate of DCh walls separately during the thruster operation. The only method that can be applied in this case is a method of optical emission spectroscopy with scanning of plasma through collimator (OESSC). According to the accepted experiment results, it is shown that criteria of thruster regime selection can be different because the regime with minimal discharge current does not coincide with the regime of minimal erosion from both of ceramics.

Author details

Andrey Vitalievich Loyan* and Alona Nikolaevna Khaustova
Scientific-Technological Center of Space Power and Engines of National Aerospace University named after N. Ye. Zhukovsky “Kharkiv Aviation Institute”, Kharkov, Ukraine

*Address all correspondence to: a.loyan@khai.edu

References

[1] Mitrofanova OA. The influence of magnitude and topology of the magnetic field on the stationary plasma thrusters integral characteristics [dissertation of a Cand.Tech.Sci: 05.07.05] Kalynynhrad: Mitrofanova Olga Alexandrovna; 2015. 147 p

[2] Titov MYu. Stationary plasma thruster integral characteristics improvement by magnetic field gradient maximization [dissertation of a Cand. Tech.Sci: 05.05.03]. Kharkov: Titov Maksim Yur'evych; 2018. 170 p

[3] Khaustova AN. Method for stationary plasma thruster outer and inner ceramic edges erosion rate diagnostics [dissertation of a Cand.Tech. Sci: 05.05.03]. Kharkov: Khaustova Alona Nikolaevna; 2018. 217 p

[4] Semenov AA. Sputtering of ceramics and ceramic composites with low energy ion flows [dissertation of a Cand. Tech.Sci: 05.07.05]. Moskov: Semenov Alexander Anatolievich; 2015. 103 p

[5] Isayev YA, Oransky AI. The method of express estimation of gas hollow cathode erosion rate and results of its approbation. In: International Electric Propulsion Conference. 1995. pp. 1408-1412

[6] Rajput RU, Khaustova AN, Loyan AV. Plasma plume diagnostics of low power stationary plasma thruster (SPT-20M8) with collisional-radiative model. The European Physical Journal Applied Physics. 2017;**78**:9. Available from: https://www.epjap.org/articles/epjap/abs/2017/04/ap160348/ap160348.html [Accessed: 25.05.17]

[7] Khaustova AN, Loyan AV. Method for the erosion rate measurements of stationary plasma thruster insulators. East European Magazine of Advanced Technology. 2017;**3/5**(87):11-17

[8] Horshkov OA, Muravlev VA, Shahayda AA. Hall Ion Thrusters for the Spcacrafts. Moskov: Mashynostroenye; 2008. 279 p

[9] Prydannykov SY. Investigation of stationary plasma characteristics during long time operation [dissertation of a Cand.Tech.Sci: 05.07.05]. Kalynynhrad: Prydannykov Serhey Yur'evych; 2003. 203 p

[10] Merkur'ev DV. Methods of increasing of the thrust characteristics of a stationary plasma thruster operating at high specific thrust impulses [dissertation of a Cand.Tech. Sci: 05.07.05]. Moskva: Merkur'ev Denis Vladimirovich; 2015. 138 p

[11] Khaustova AN, Loyan AV, Rybalov OP. Development of optical receiver for erosion rate measurements of gas discharge chamber external and internal ceramics separately. Engineer's Bulletin. 2015;**2**:29-36

[12] Khaustova AN, Rybalov OP. OESSK method instrumentation facility and diagnostics method of stationary plasma thruster edge insulator wear. Engineer's Bulletin. 2016;**2**:212-220

[13] Pagnon D, Pellerin S, Dudeck M, Maksimenko TA, Koshelev NN, Loyan AV. Optical emission spectroscopy measurements on a SPT-20 Hall Effect Thruster on the KhAI ground test facility. Aviatsionno-kosmicheskaya tekhnika i tekhnologiya. 2006;**10**(36): 117-122

[14] Loyan AV, Maksimenko TA, Rybalov OP. 1500 hour lifetime test of SPT-20 and comparison with optical emission spectroscopy of plume. In: 31st International Electric Propulsion Conference (IEPC-2009); 20-24 September 2009; University of Michigan. USA; 4 p

[15] Rajput RU, Khaustova AN, Loyan AV. Development of xenon collisional radiative model for plasma diagnostics of hall effect thrusters. East European Magazine of Advanced Technology. 2017;**28**(86):24-29