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The low-current cathode for a small power electric propulsion

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Abstract
A cathode with low discharge current and low flow rate was designed and experimentally investigated. The general idea was to minimize a heat loss in the cathode body. The cathode had a classical configuration. An emitter was a porous tungsten insert impregnated with a mixture of BaO-CaO-Al_2O_3. The specific feature of the cathode was the design of both the emitter unit and the heater unit. The cathode was tested with the main discharge currents from the range of 0.09 – 0.30 A. Xenon flow rate was varied from 0.015 to 0.080 mg/s. The keeper discharge was used to maintain the thermal regime of the emitter during the operation of the cathode. The power of the keeper discharge was at the level of 10 W during the test.

1. Introduction

Today there is a growing interest in small satellite vehicles globally. Small satellite vehicles have emerged due to the miniaturization of the electronic and component base and its reduced costs. One of the specific features of such satellite vehicles is the small capacity of an on-board power plant. Electric propulsion systems can be used to propel such vehicles. The main advantage of such systems is high specific impulse.

In order to enable electric propulsion ion and Hall thrusters, a cathode must be created which allows to neutralize the charge of the plasma plume emitting from the thruster, with typical current values up to 0.5 A. Such low current cathodes must be developed taking into account a number of specific considerations: this article describes approaches used in developing low-current cathodes, the principle circuit diagram of the developed, test procedures and test results.

2. Development of cathode design

2.1. Requirements for developed cathode

In order to solve the task of creating small-capacity Hall and ion thrusters, a task was set to develop a low-current cathode with characteristics presented in Table 1.

Table 1: Requirements for cathode characteristics

Parameter	**Value**
Current range, mA	from 90 to 300
Propellant	Xenon
Nominal flow rate of propellant, mg/sec	not more than 0.03
Keeper discharge power, W	not more than 10

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2.2. Specific considerations in developing low-current cathodes

The main issue in developing low-current cathodes is the complexity of maintaining the operating temperature of the emitter under stationary operating conditions.

The operation of the majority cathodes for ion and Hall thrusters consists in obtaining electrons from the solid-state body. Thermionic emission is used to obtain electrons. This phenomenon is described by Richardson–Dushman equation:

$$j = AT^2 \exp\left(-\frac{e\varphi_0}{kT}\right) \quad \textbf{(1)}$$

where j is the electron current density emitted at emitter temperature T; A is a universal constant with a value of 120 $A \cdot cm^{-2} \cdot K^{-2}$; e is the elementary charge; φ_0 is the work function of emitter material; k is the Boltzmann constant.

As it is seen from the equation (1), the main factor for obtaining electron current is the surface temperature of the emitter. To maintain the emitter temperature which is necessary to ensure that the required electron current is obtained, energy must be supplied.

Modern electric propulsion cathodes are plasma devices. Some portion of the thruster propellant is injected through the surface of an emitter. The propellant is ionized when interacting with emitted electrons. Plasma inside the cathode performs two main functions.

1. Transporting energy from the discharge power supply to the emitter surface by bombarding with charged particles.

2. Reducing the energy losses arising due to transport of electrons from the surface of the emitter to the plasma plume or the discharge chamber.

Therefore, the emitter of modern cathodes receives energy from the power supply of the thruster discharge by interacting with cathode plasma. The temperature set on the surface of the emitter depends on the balance between the deposited and extracted energy. In other terms, the energy balance can be presented in the form:

$$Q_{in} = Q_{em} + Q_{out} \quad \textbf{(2)}$$

where Q_{in} is the amount of heat supplied to the emitter from plasma; Q_{em} is the amount of heat extracted from the emitter in the process of electron emission; Q_{out} is the emitter cooling by thermal conductivity and radiation.

The heat supplied to the emitter from the plasma is proportional to the discharge current and the consumed energy coefficient.

$$Q_{in} = IU_{in} \quad \textbf{(3)}$$

where I is discharge current; U_{in} is the coefficient of energy consumed to heat the emitter.

The experience in testing cathodes at Keldysh Research Center in a discharge current range from 2 to 120 A shows that the coefficient of consumed energy for cathodes is at the level of the first ionization potential of the propellant. The first ionization potential for xenon is equal to 12 V, while the coefficient of consumed energy falls within the estimated range from 8 to 15 V.

The heat extracted from emitted electrons is determined by the number of electrons and their energy. The average energy of the electrons that have left the emitters is a function of two components: effective work function and emitter temperature. Ignoring the Schottky effect, the effective electron work function will be equal to the work function of the material.

$$Q_{em} = I\left(\varphi_0 + \frac{3}{2}\frac{kT}{e}\right) \quad \textbf{(4)}$$

For the current ranges specified in Table 1, the energy, which will be available to ensure the operating temperature of the emitter, can be estimated from the above relationships.

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$$Q_{out} = I\left(U_{in} - \varphi_0 - \frac{3}{2}\frac{kT}{e}\right) \quad \mathbf{(5)}$$

The emitter of the developed cathode is made of porous tungsten impregnated with barium, calcium and aluminium compounds. This type of emitter material is used for the majority of cathodes of ion and Hall thrusters. The main advantage of this type of emitters is relatively low operating temperature which is particularly relevant to low-current cathodes. The work function for this type of emitter is 2,05 eV at surface temperature 1050 °C. Consequently, the design value of heating power, which can be used to heat the emitter to the operating temperature, is shown in Figure 1.

The emitter produces 0.5 W with the minimum required current from the operating range in the case it falls on the lower heat curve (see Figure 1). In order to heat the emitter with such power, diverging heat from its surface needs to be practically excluded by both thermal conductivity and radiation. In other words, there should be created an ideal heat insulation of the emitter against the structural elements of the cathode. Besides, it is necessary to increase the heat transfer on the emitter surface from the plasma, i.e., ensure that the cathode operates on the upper heat curve (see Figure 1).

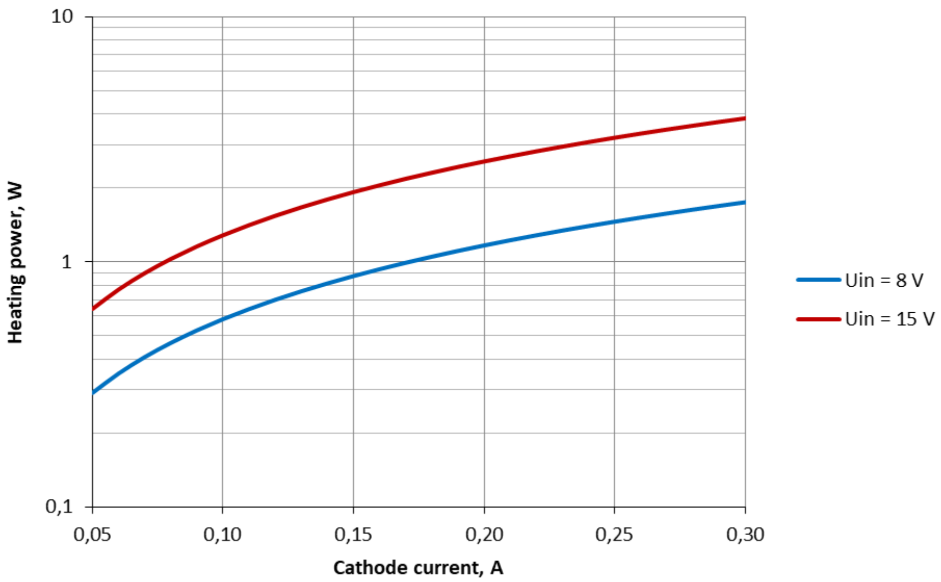

Figure 1: The value of heating power which is deposited on the emitter surface

If we stay in the framework of the traditional structural scheme of the cathode in which the emitter made as a hollow cylinder is closely fitted to the cathode tube, the wall thickness of the cathode tube needs to be reduced. And to minimize the contact of the cathode tube with other structural elements of the cathode. Besides, the cathode tube must be fabricated of a material with a low thermal conductivity factor.

There is a structural limitation on the minimum thickness of the cathode tube wall. The design of cathode tube must be ruggedized to withstand loads arising when the cathode is launched into space by a launcher.

Apart from the above problem of ensuring the emitter is heated, low-current cathodes have another significant problem. This problem consists in minimizing the energy required to transport electron current from the emitter surface to the cathode outlet and further to the discharge channel of the thruster or to the plasma plume flowing out of the thruster. This problem arises because of failure to carry out, to the full extent, geometry scaling of the main dimensions of the plasma regions of well-proven cathode designs. This limitation is due to the technological capabilities of creating small orifices in thick blanks made of hard-to-machine refractory metals.

In low-current cathodes these problems are addressed by increasing the electron current issued by the emitter and by creating keeper discharge between the emitter and the keeper electrode. As a rule, keeper current exceeds the required discharge current. The creation of keeper discharge leads to additional energy losses and to reducing the energy efficiency factor of the thruster. For instance, the main discharge current is 329 mA, while keeper current is 900 mA and keeper power is approximately 17 W [1] in the cathode neutralizer of the ion thruster T5 (UK-10) with a thrust of 18 mN.

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2.3. Selecting cathode structural scheme

Based on the conclusions made in the previous section, an idea of the constructive scheme of the cathode was formed. It was decided to reduce the heat contact of the insert with the cathode tube by reducing the contact area and exclude the contact of the hot region of the emitter unit with other elements of the cathode. In particular, in the most generic cathode scheme the start heater is wound on the cathode tube and the heat from the heater is transported to the emitter by thermal conductivity. This scheme is used in the cathodes of the ion thruster NSTAR [2]. At the same time, in the discharge mode when the heater is switched off, it is an additional element over which the heat is extracted from the emitter and distributed over cathode design. In the developed cathode, it was decided to transfer heat from the heater to the emitter unit by radiation by providing a gap between the heater and the cathode tube.

To assess the correctness of the decisions taken and to determine the value of keeper current, a heat calculation has been carried out for the design of the emitter unit. The relationships of the heat radiation powers in various cathode elements interacting with plasma has been set on the basis of the work [3]. This work gives a classification of various types of cathodes depending on the type of the emitter heating mechanism. It was also established that the emitter heating mechanism depends on the geometry of the cathode orifice plate, namely, on the diameter and length of the orifice.

In developing the cathode it was decided to determine the type of cathode by current density in the orifice. The work [3] divides cathodes into three types. The types are described on the example of three cathode designs. On the basis of the data contained in the above work we can assess current density in the orifices of various types of cathodes. The assessment of current density in the orifices of various types of cathodes is presented in Table 2.

Table 2: Current density in the orifice for various types of cathodes

Type of cathode	**Current density, A/cm^2**
Type A	4600
Type B	1900
Type C	480

Current density in the orifice considering only the main discharge (refer to Table 1) lies in a range from 150 to 450 A/cm^2. With such values the developed cathode belongs to type C.

In Type C cathodes heat is distributed along the substantial part of the emitter and only a small amount of heat is deposited to the internal surface of the orifice plate and in the orifice [3]. The relationship of heating power in various regions of the emitter unit of Type C cathodes is presented in Table 3.

Table 3: Depositing heat in the emitter unit of a Type C cathode.

Deposited heat region	**Heating power %**
Orifice	3
Internal surface of the orifice plate	7
Emitter	90

The calculation has been carried out in SolidWorks Simulation 2010 SW until the stationary heat condition was achieved. Heat was deposited to the internal surfaces of the emitter unit. The deposited heat was distributed to the structural elements in the proportion specified in Table 3. Heat is extracted from the emitter unit structure by radiation with an emissivity factor on the end surface of the cathode tube equal to 1. The emissivity factor on the other external surfaces is taken as equal to 0.5. Energy is exchanged between the internal elements of the emitter unit by thermal conductivity and radiation. The heat exchange coefficient by radiation was taken as equal to 0.5. Heat contact between parts in the model is ideal. Figure 2 shows temperature distribution in the emitter unit structure with the total heating power of 0.5 W. This power value corresponds to the cathode work with the minimum discharge current of 0.09 A.

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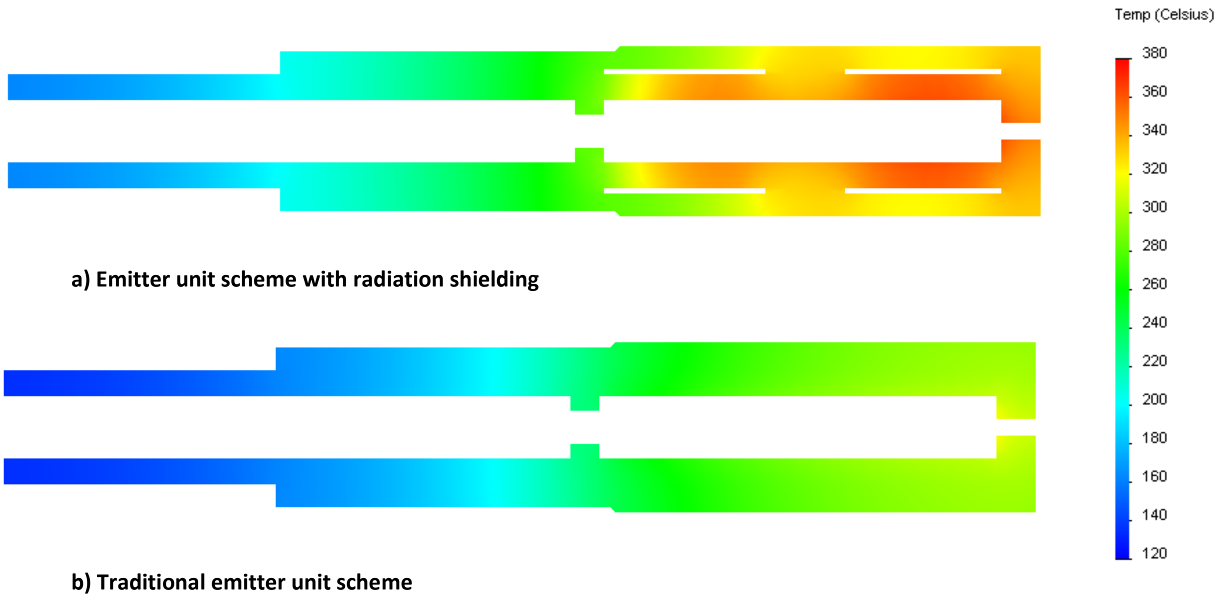

Figure 2: Temperature distribution in the emitter unit at the heating power of 0.5 W.

For comparison, Figure 2 shows the calculation results of two configurations of the emitter unit with emitter radiation shielding (Figure 2a) and traditional emitter unit scheme (Figure 2b). As we can see, the presence of a gap between the emitter and cathode tube allows to increase emitter temperature by 60 °C on the average. Calculation results show that the average temperature of the internal surface of the emitter is 343 °C and 283 °C with or without shielding respectively.

Impregnated tungsten emitters ensure a long service life in a temperature range from 950 to 1250 °C. If the temperature is below 950 °C, this type of emitter does not allow operating in electron emission self-maintenance mode. Therefore, emitter shielding offers certain advantages in terms of temperature, however it does not allow the operating temperature range to be achieved at the minimal discharge current.

The selected cathode configuration can help achieve the thermal mode of the operation by increasing emission current by the means of creating keeper discharge between the emitter and keeper electrode. To determine the required heating power, we have conducted a series of emitter unit calculations. The calculations were carried out until the operating temperature range of the emitter was achieved by sequentially selecting the heating power. If the heating power is 5 W, the average surface temperature of the emitter amounted to 990 °C. Temperature distribution in the emitter unit at the heating power of 5 W is presented in Figure 3.

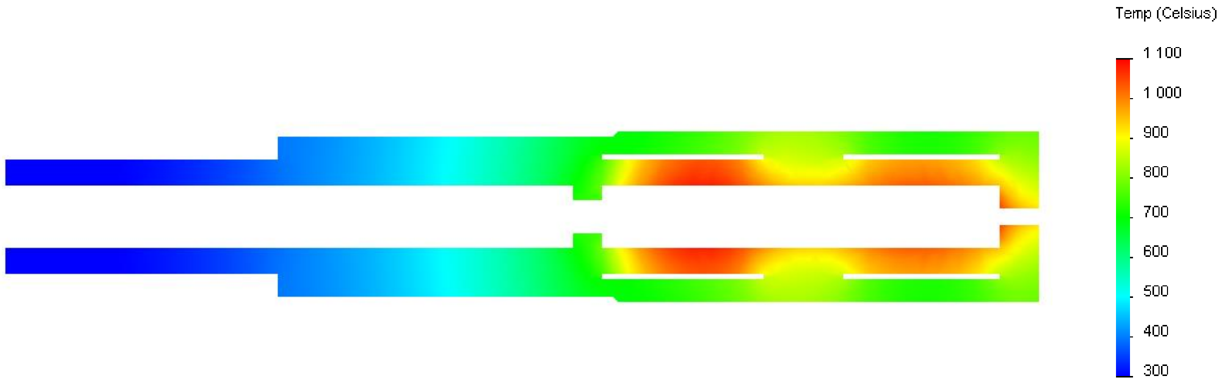

Figure 3: Temperature distribution in the emitter unit at the heating power of 5 W

If the discharge current is derived from the equation (5), the keeper current range can be evaluated. The selected emitter unit configuration must be operable at an emission current in a range from 0.39 to 0.86 A. Therefore, the keeper current at the minimal discharge current of 0.09 A must be within a range from 0.30 to 0.77 A. If this cathode is used

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as a cathode neutralizer for ion thrusters, it must meet an additional requirement: to function for a long period of time with only keeper discharge, in this case keeper current is limited by a range of 0.39 – 0.86 A.

The work resulted in a cathode whose appearance is depicted in Figure 4.

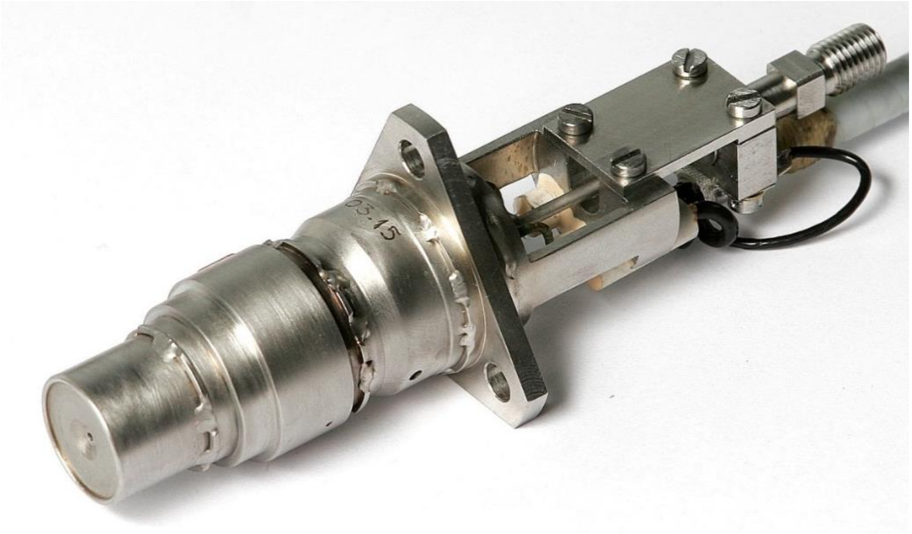

Figure 4: The appearance of the low-current cathode

3. Experimental procedure

The experimental study of the low-current cathode was performed to solve the following tasks.

1. Specification of the cathode start heater parameters.
2. Determination of keeper discharge characteristics.
3. Determination of main discharge characteristics.

To start the cathode, it is necessary to heat the emitter to reach the operating temperature range in which electron emission occurs. Once electrons appear in internal cavities of a cathode, it is important to carry out gas breakdown to trigger the ionization process. The start heater of the cathode is used during emitter heating. A voltage of 300 V is supplied between the emitter and keeper electrode to carry out gas breakdown. Once the ionization process has commenced, the start heater is switched off. The main characteristic of the start heater is its power. The first part of the experimental study is aimed at specification the heater power required to start a cathode.

In order to determine the characteristics of the keeper discharge, which were discussed in the previous section, the parameters of the main discharge and keeper discharge of the cathode were determined at a xenon flow rate of 0.03 mg/sec. The main discharge current varied in a range from 0.09 to 0.30 A (refer to table 1), while keeper current varied in a range from 0.2 to 0.7 A. Besides, keeper current was selected on the assumption that the cathode must remain in operable condition without the main discharge, i.e., only with the presence of keeper discharge to the keeper electrode.

The characteristics of the main discharge were determined after completing the previous stage of experimental study, i.e., after the keeper current had been selected. The purpose of this stage was to determine the optimum xenon flow rate to ensure cathode performance. This stage consisted in obtaining cathode characteristics in a discharge current range from 0.09 to 0.30 A and in a propellant flow rate range from 0.015 to 0.08 mg/sec.

Experimental study of the cathode was carried out under conditions that were close to actual operating conditions of the cathode. For this purpose, a vacuum facility specifically designed for cathode testing was used. The cathode was placed inside a vacuum chamber whose volume is 0.29 m^3. The vacuum facility is equipped with a cryogenic pump with an air pumping performance of 6.5 m^3/sec and xenon pumping performance of 3.05 m^3/sec. The pump ensures pressure in the vacuum chamber without feeding propellant $5 \cdot 10^{-4}$ Pa. With the xenon flow rate of 0.03 mg/sec the pressure in the vacuum chamber is at the level of $1 \cdot 10^{-3}$ Pa.

A laboratory anode is used to carry out self-sufficient cathode tests. The anode imitates the plasma plume issuing from the thruster or plasma of the discharge chamber of the thruster. The main discharge of the cathode is created between the emitter and anode. An anode in the form of a perforated flat plate with holes 6.5 mm in diameter was used to test the low-current cathode. The anode was installed at a distance of 6 mm from the end of the keeper electrode of the cathode.

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The experimental facility is equipped with a propellant supply system, a cathode power supply system and a cathode performance measurement system. The propellant supply system is designed to set xenon flow rate through the cathode in a range from 0.01 to 0.75 mg/sec. The cathode power supply system consists of regulated laboratory DC sources that are stabilized by current and by voltage. The cathode power supply system includes three power supplies: heater power supply, keeper discharge power supply and main discharge power supply.

Emitter temperature is evaluated by means of optic measurements of orifice plate temperature. It is due to the fact that the emitter is hidden by structural elements from optic instruments. The orifice plate is in direct contact with the emitter and has a relatively small thickness. For this reason, at first approximation, we can assume that the temperature of the external surface of the orifice plate is equal to the temperature of the emitter. An optical pyrometer was used to measure the temperature of the orifice plate of the emitter unit.

4. Test results and discussion

4.1. Starting the cathode

Based on the results of 15 cathode starts with a xenon flow rate of 0.03 mg/sec it was established that the cathode was stably started at a heater power of around 70 W. This being the case, cathode heating takes around 5.5 minutes. The temperature of the orifice plate at the start moment was equal to 1200 °C.

4.2 Keeper discharge

The main characteristic of the keeper discharge is keeper power. The values of the keeper power depending on the main discharge current with different keeper currents are presented in Figure 5.

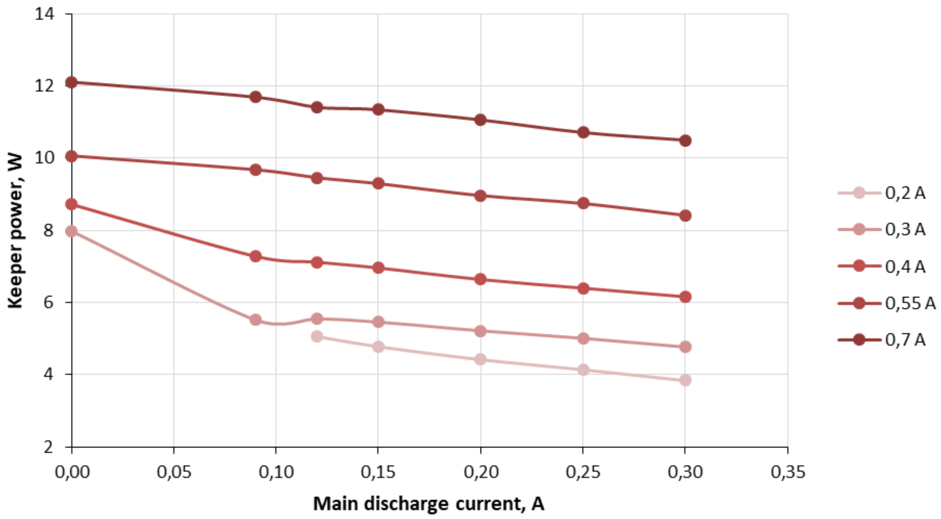

Figure 5: Keeper power

Only those keeper currents that are below 0.55 A meet the technical requirements (refer to Table 1) that limits keeper power by a value not exceeding 10 W. If the keeper current is 0.2 A, cathode discharge extinction occurs with no main discharge current present and operates in an unstable manner with the main discharge current of 0.09 A. If the operation is unstable in this mode, keeper voltage exceeds 30 V, discharge pulsations start to develop which eventually leads to discharge extinction. If the keeper current is 0.3 A, the cathode operates in a stable manner for each studied main discharge current. However, if the operating mode is switched from the main discharge current equal to 0 A to the discharge current equal to 0.09 A, cathode discharge extinction occurs. If keeper currents are equal to 0.4 and 0.55 A, the discharge in the cathode burns stably in all studied operating modes.

When analyzing the current-voltage curve of the main and keeper discharge, an interesting fact was discovered. Keeper voltage does not depend on the ratio of the main discharge current and keeper current, but it depends on the total cathode current. The same applies to the main discharge voltage, except voltages at low main discharge currents. An interesting fact is that if the main discharge current is 0.09 A, the main discharge voltage in some modes is lower than keeper voltage. Figure 6 shows main discharge voltage and keeper voltage depending on cathode current.

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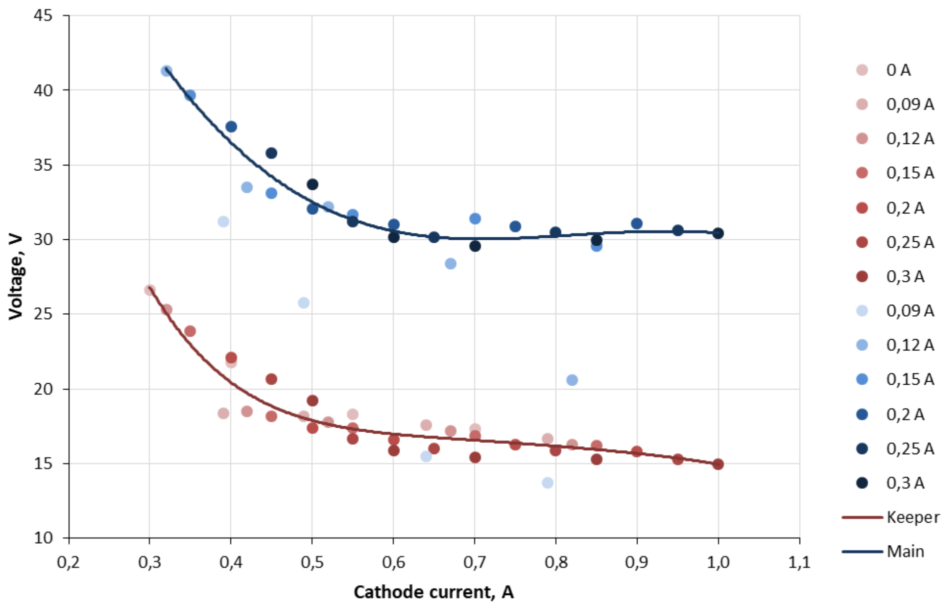

Figure 6: Main discharge voltage and keeper voltage

The current of 0.4 A has been selected as a keeper current. With this current the cathode operates in a stable manner over the entire range of the main discharge currents with minimum losses of additional power. Besides, this keeper current is in the current range which was determined in section 2.3.

4.3 Main discharge

To determine an optimum propellant flow rate which will allow the cathode to work stably over the entire range of the main discharge current, it is essential to determine criteria for comparing operating modes. For this purpose, two characteristics of the cathode-operating mode were selected. The first one is discharge voltage. Discharge voltage reflects energy losses to transfer electron current from the emitter to the plasma plume or the discharge chamber and, partially, to obtain electrons from the emitter. The second one is current fluctuations in the cathode circuit, which reflect discharge ignition stability. The root-mean-square deviation (RMS) was used as a measure of discharge ignition stability. The value of keeper power was used as additional criterion which may limit the selection of the propellant flow rate.

Figure 7 shows the dependence of the main discharge voltage on the propellant flow rate for various main discharge currents, with keeper current being 0.4 A. If propellant flow rates are 0.04 and 0.08 mg/sec, the main discharge voltage is in a narrow range from 25 to 33 V. If xenon flow rate is reduced to 0.035 mg/sec, the main discharge voltage begins to rise. The value of voltages ranges from 28 to 35 V. If xenon flow rate continues to decrease to 0.015 mg/sec, there is a difference in the behaviour of voltage curves depending on the value of the main discharge current. With main discharge currents of 0.23 and 0.30 A voltages increase twofold reaching 50 V. At the same time, at low currents of 0.09 and 0.12 A the voltage drops to 20 V.

Figure 8 shows the dependence of the share of the RMS of the cathode current on the main discharge current with various propellant flow rates. The share of the RMS of the cathode current is expressed by the ratio of the RMS of the cathode current to the cathode current value in this operating mode. If the current is 0.09 A over the entire studied range of xenon flow rates, the RMS of the cathode current does not exceed 5% of the cathode current. If the main discharge current increases with propellant flow rates above 0.035 mg/sec, there is an increase of cathode current fluctuations. Cathode current fluctuations reach the maximum with discharge currents of 0.16 A, the amplitude is 20% from the cathode current which amounts to 0.12 A. In this mode the amplitude of cathode current fluctuations is comparable to the main discharge current. If the discharge current increases, cathode current fluctuations with flow rates above 0.03 mg/sec are decreased to 15%. If propellant flow rates are below 0.02 mg/sec, there is an increase in fluctuations only provided when the current exceeds 0.16 A.

Keeper discharge power does not exceed 10 W over the entire studied range of propellant flow rates. For this reason, this criterion does not impose any restrictions on the selection of xenon flow rate through the cathode. The dependency of keeper power on the main discharge current is depicted in Figure 8.

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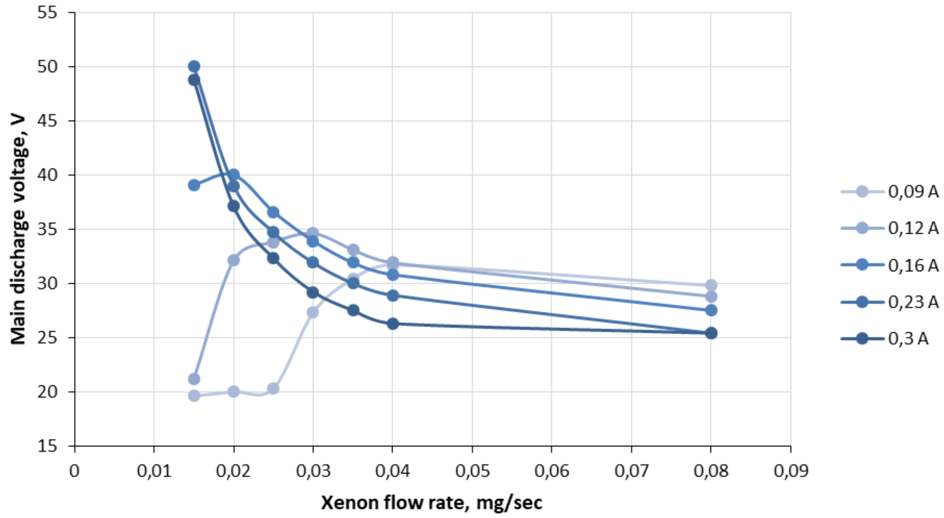

Figure 7: Main discharge voltage

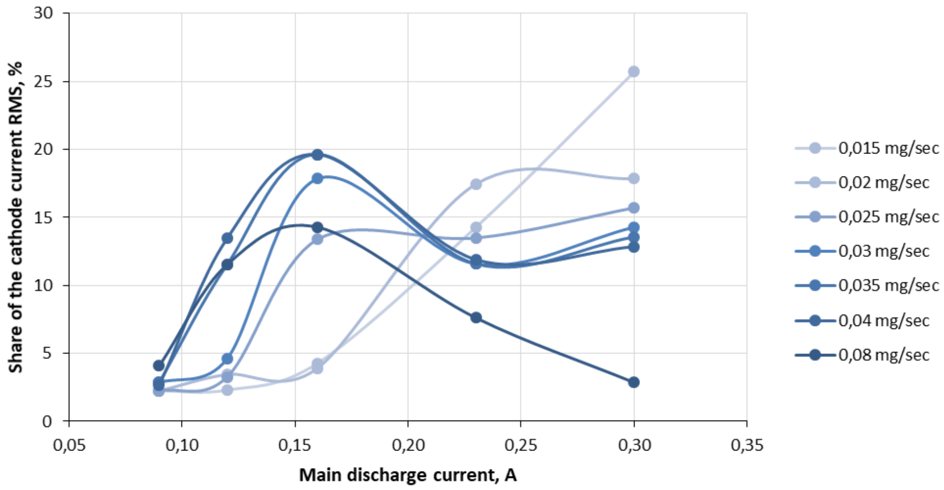

Figure 8: The share of the cathode current RMS deviation

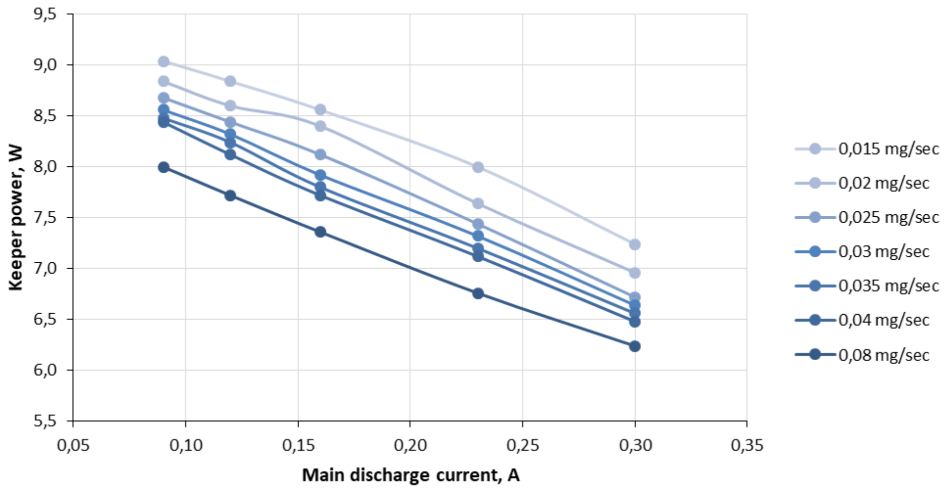

Figure 9: Keeper power

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From the point of view of cathode current fluctuations, it is more logical to select the operating xenon flow rate equal to 0.025 mg/sec. With this flow rate, fluctuations in the operating range of the main discharge currents do not exceed 16% of the cathode current value. But from the point of view of the main discharge voltage at a propellant flow rate of 0.04 mg/sec, minimum energy is spent to transfer electrons from the emitter to the plasma plume or the discharge chamber. But this flow rate does not fall in the permissible range of xenon flow rate (refer to Table 1). Also, the additional propellant flow rate through the cathode reduces the specific impulse of the thruster which is specifically relevant to low-power thrusters. As an operating point, a maximum permissible xenon flow rate to the cathode is equal to 0.03 mg/sec.

Figure 10 shows a photo of low-current cathode operation during test campaign.

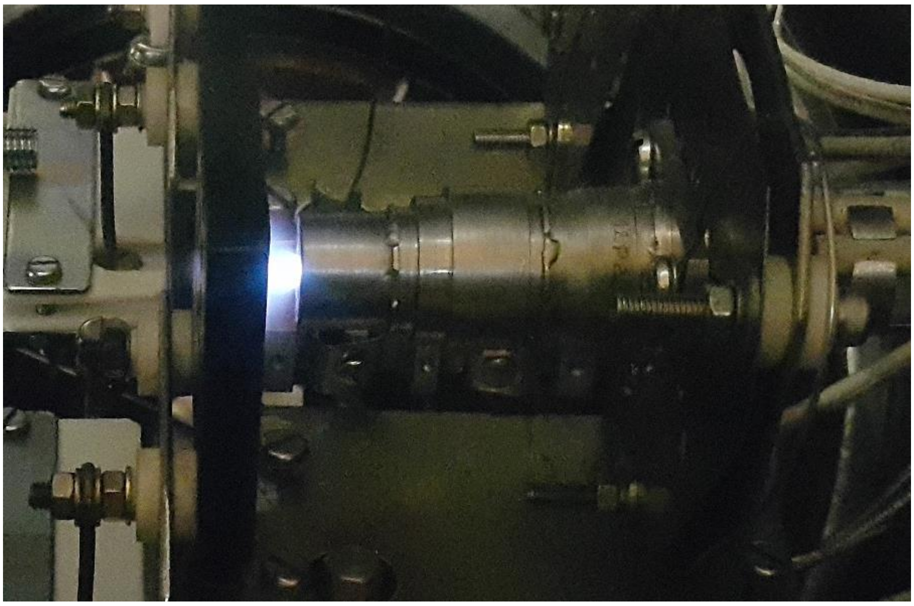

Figure 10: Low-current cathode under test campaign

4.4. Further directions of low-current cathode developments

One can identify two main directions for development of low-current cathodes operating at currents up to 0.5 A. The first direction is related to reducing keeper power all the way to creating cathodes operating without keeper discharge. The development of this direction requires ensuring the required thermal mode of the emitter at small values of heating power. This could be problematic in the proposed cathode configuration, but further steps can be made in the designated direction of the heat insulation of the emitter against the structural elements. The second direction is related to reducing the propellant flow rate. The transfer of the charge of the main discharge by the propellant in the developed cathode is in a range from 3 to 10 C/mg, this value of modern cathode amounts to 30 C/mg. The main problem that blocks implementation of this direction is related to the technology for machining of refractory materials. For instance, to reduce propellant flow rate, it is necessary to reduce the diameter of the orifice. Today a number of difficulties exist in fabricating orifices that are less than 0.3 mm in diameter in refractory metals, such as molybdenum and tungsten.

5. Conclusion

This works has stated the specific considerations in developing low-current cathodes for ion and Hall thrusters. A simple method is proposed to evaluate the power released in the emitter unit of the cathode. This evaluation is used to develop the scheme for the emitter unit of the cathode. The developed scheme has led to the creation of a cathode for low-power ion and Hall thrusters. The cathode has undergone self-sufficient tests in the main discharge current range from 0.09 to 0.30 A with propellant flow rates from 0.015 to 0.080 mg/sec. The cathode demonstrates stable performance with a keeper current of 0.4 A and with the keeper power not exceeding 10 W.

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