PARAMETERS OF THE ST-40M HALL THRUSTER WITH INCREASED POWER DISCHARGE SUPPLY
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Abstract. The article presents the results of experimental investigation of the ST-40M Hall thruster modification developed by the Space Electric Thruster Systems (SETS). The thruster used a new filament hollow cathode with an emitting insert made of lanthanum hexaboride (LaB6). The use of a new hollow cathode made it possible to study the thruster’s parameters in the discharge power range of 300 – 550 W. The investigation was carried out using a stabilized voltage supply as a discharge power supply. As a result of experimental investigation, the current-voltage characteristics of the discharge in the accelerating channel of the thruster were obtained at fixed values of the anode’s mass flow rate of the working gas - xenon. The experimental dependences of thrust on the anode’s mass flow rate of the working substance and the discharge voltage, as well as the dependences of the specific impulse and thruster efficiency on the discharge voltage, are obtained. Experimental studies have shown that with a change in the discharge voltage in the range of 250 – 400 V and a change in the mass flow rate of the working gas in the range of 0.9 – 2.2 mg/s, the thruster provides a thrust value of 12 – 33 mN, a specific impulse value of 1200 – 1800 s, and the maximum value of the anode’s efficiency is 48 – 52%. The article also contains oscillograms illustrating the repeated process of the thruster starting. Experimental investigation of the modified thruster ST-40M with the new hexaboride hollow cathode showed a significant improvement in thruster parameters compared to the prototype parameter before modification. In the process of experimental investigation, it was found that in some modes of the thruster operation, significant fluctuations in the discharge current occur, which led to a significant decreasing in the thruster parameters. For a more accurate clarification of the nature and parameters of the discharge current oscillations, it is necessary to conduct additional studies. The obtained experimental parameters of the modified ST-40M thruster made it possible to determine the values of its optimal parameters for various space missions.

Keywords: HALL THRUSTER, CYCLOGRAM OF THE HALL THRUSTER START, FILAMENT LaB6 HOLLOW CATHODE, OPTIMAL PARAMETERS, DISCHARGE CURRENT FLUCTUATIONS.

ПАРАМЕТРИ ST-40М ХОЛОВСЬКОГО ДВИГУНА З ДЖЕРЕЛОМ РОЗРЯДУ ПІДВИЩЕНОЇ ПОТУЖНОСТІ

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Анотація. В статті представлені результати експериментальних досліджень модифікації Холловського двигуна ST-40М, розробленого в компанії Electric Thruster Systems (SETS). У складі двигуна використовувався новий накальний катод з емітуючою вставкою з гексабориду лантану (LaB6). Використання нового полого катоду дозволило досліджувати параметри двигуна в діапазоні потужності розряду 300 – 550 Вт. Дослідження проводились з використанням в якості джерела електроживлення ланок розряду стабілізованого джерела напруги. В результаті експериментальних досліджень отримані вольт-амперні характеристики розряду в прискорювальному каналі двигуна при фіксованих величинах масових витрат робочого газу - ксенону. Наведені експериментальні залежності тяги від масових витрат робочої речовини та напруги розряду, а також залежності величини питомого імпульсу і ККД двигуна від напруги розряду. Експериментальні дослідження показали, що при зміні напруги розряду в діапазоні 250 – 400 В та зміні масових витрат робочого газу в діапазоні 0.9 – 2.2 мг/с двигун забезпечує величину тяги 12 – 33 мН, величину питомого імпульсу 1200 – 1800 c, а максимальне значення ККД двигуна складає 48 – 52%. У статті також наведені осцилограми, які ілюструють багатократний процес запуску двигуна. Експериментальні дослідження модифікованого двигуна з новим гексаборидним катодом показали суттєве підвищення параметрів двигуна у порівнянні з параметрами його прототипу до модифікації. В процесі експериментальних досліджень було встановлено, що на деяких режимах роботи двигуна виникають значні коливання розрядного струму. Коливання розрядного струму призводять до значного погіршення параметрів двигуна. Для більш точного встановлення характеру та параметрів коливань розрядного струму необхідне проведення додаткових досліджень. Отримані експериментальні параметри модифікованого двигуна ST-40М дозволили визначити значення його оптимальних параметрів для різноманітних космічних місій.

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Abbreviations
Nd – discharge power;
Ud – discharge voltage;
Id – discharge current;
Iem1 – current of the internal coil of the electromagnet;
Iem2 – current of the external coils of the electromagnet;
Ih – current heater of the hollow cathode;
Uk – voltage of the hollow cathode’s keeper;
$m_1$ – main mass flow rate to the thruster’s anode unit;
$m_2$ – mass flow rate to hollow cathode;
T – thrust of the thruster;
Isp – specific impulse;
E – efficiency of the anode unit;
C – cost of the thrust.

Introduction
The ST-40 Hall thruster was designed to operate as part of the SPS-40 electric propulsion system at the input power in the range of 250 – 300 W [1–3]. With a given power consumption, this thruster insured the thrust of 13 - 15 mN and provided a specific impulse of 1200 - 1300 s.

A feature of the ST-40 Hall thruster was the use of a non-heater hollow cathode with an emitting insert material based on barium salts [2, 3]. The use of a non-heater hollow cathode in the thruster made it possible, on the one hand, to exclude the cathode heating power supply from the Power Processing Unit (PPU) of the electric propulsion system.

On the other hand, the use of a non-heater cathode necessitated the use of a high-voltage power supply for the keeper of hollow cathode with a voltage level of 1100 - 1200 V. In the process of the ST-40 Hall thruster testing and the testing of the SPS-40 electric propulsion system, the developers encountered a number of problems related to starting the thruster and the stability of its parameters and operation [2, 3].

The problem statement of this research was to experimentally determine the algorithm for the thruster starting; determine the main parameters of the thruster: thrust, specific impulse and anode efficiency; as well as the main characteristics of the thruster at a discharge input power of 300 - 550 W at a change of the anode mass flow rate of the working substance (Xe) and the value of a discharge voltage.

Solution of the research problem
Laboratory facility. Experimental investigation of the modified ST-40M Hall thruster was carried out in a vacuum chamber (Fig. 2), equipped with cryogenic vacuum panels – Coolpak 6000H. The initial pressure in the chamber did not exceed 2·10^{-6} Torr. At the maximum mass flow rate of the working gas into the thruster, the pressure in the chamber did not exceed 2.5·10^{-5} Torr. 

Figure 1 – LaB6 hollow cathode with the heater for ST-40M

The ST-40M Hall thruster was designed to operate as part of the SPS-40 electric propulsion system at the input power in the range of 250 – 300 W [1–3]. With a given power consumption, this thruster insured the thrust of 13 - 15 mN and provided a specific impulse of 1200 - 1300 s.

A feature of the ST-40 Hall thruster was the use of a non-heater hollow cathode with an emitting insert material based on barium salts [2, 3]. The use of a non-heater hollow cathode in the thruster made it possible, on the one hand, to eliminate these problems, SETS developed the hollow cathode with heater and the LaB6 material as emitting insert [4], which is shown in Fig. 1. The use of a new cathode for modified ST-40M thruster made it possible to significantly facilitate the process of the thruster starting and ensure its operation at a higher level of discharge input power [5, 6].
To supply the mass flow rate of the working gas to the anode unit of the thruster - $m_1$ and the hollow cathode – $m_2$, the laboratory feeding supply system was used. The accuracy of the mass flow rates of the working gas to the anode unit and cathode was ±3%. In the process of experimental investigation, the mass flow rate of the working gas ($m_1$) varied from 0.9 to 2.2 mg/s with a step of 0.1 mg/s. The mass flow rate of the working gas through the cathode ($m_2$) during the experimental investigation was constant and amounted to 0.15 mg/s.

![Figure 2 – The vacuum chamber for experimental investigation](image)

An adjustable source of stable voltage – TDK Lambda GEN600-2.6 was used as a discharge power supply. The discharge voltage $U_d$ varied from 225 to 400 V in steps of 25 V. To set and change the magnitude of the currents through the internal and external coils of the thruster’s electromagnets, two sources of stable current were used – Uni-T 3315TFL-II.

In the process of carrying out experimental investigation, the discharge current was minimized while maintaining the biggest thrust value by selecting the values of the currents flowing through the internal $Iem_1$ and external coils $Iem_2$ of the thruster’s electromagnets.

During the ST-40M testing, the value of the thrust was measured by the specially designed and calibrated thrust measurement device, which ensured the measurement of the thruster’s thrust in the range from 10 to 35 mN with an accuracy of ±4%.

**Object of investigation.** The general view of the modified ST-40M Hall thruster with a lanthanum hexaboride cathode is showed in Fig. 3. A feature of the modified Hall thruster design is the use of a magnetic shield application to increase the steepness of the change in the magnetic field induction along the acceleration channel, as shown in Fig. 4.

When setting the tasks of studying the ST-40M thruster, it was noted that starting the thruster when it was operating with a non-heater cathode and a power consumption level of 200–300 W was carried out with certain difficulties, and in some modes, fluctuations in the discharge current occurred, which led to a significant decrease in the thruster performance [2, 3].

![Figure 3 – The general view of the modified ST-40M thruster](image)

Therefore, at the first stage of the research, the question of the algorithm for the thruster starting was studied when it was operating with a filament hexaboride cathode and the discharge input power in the range of 400 – 550 W.

**Investigation of the thruster starting.** In the process of preparing the thruster for operation, the hollow cathode is launched. For this purpose, a current $Ih = 4.5$ A was supplied to the cathode heater, the mass flow rate of the working gas through the cathode was $m_2 = 0.17$ mg/s, and the voltage to the keeper $Uk = 400$ V. At the same time, the discharge voltage $Ud = 300$ V was applied to the anode, and the external and inner coils of the thruster are supplied with currents $Iem_1 = 0.9$ A, $Iem_2 = 0.85$ A.

After the emitter insert of the hollow cathode reaches the operating temperature, an internal discharge is ignited and the keeper voltage drops to 20 – 25 V. The drop in the voltage of the keeper indicates that the cathode
is ready for operation, after which the main mass flow rate of the working gas is supplied to the thruster’s anode $m_1 = 1.7$ mg/s and the thruster is started.

Oscillogram of the process of the ST-40 thruster starting during its operation with a lanthanum hexaboride hollow cathode and a discharge power of 300 – 550 W are shown in Fig. 4. During the first stage of the research, several dozens of successful thruster’s starts/stops were carried out in accordance with the specified cyclogram, while no failures to the thruster start were found.

**Determination of the thruster parameters.** At the second stage investigation, to determine the optimal operating modes and regimes of the ST-40M Hall thruster, its parameters were determined when the discharge voltage changed in the range of 250 – 400 V and the anode working gas mass flow rate varied from 0.9 to 2.2 mg/s.

To estimate the degree of ionization of the working gas in the accelerating channel, the experimental current-voltage characteristics of the thruster were determined, which are shown in Fig. 5.

An analysis of the obtained current-voltage characteristics shows that in almost the entire range of the discharge voltage and the main flow rate of the working gas, most of the characteristics have a positive slope, which indicates an insufficient degree of ionization of the working gas in the accelerating channel and the need to optimize of the thruster magnetic system.
One of the most important characteristics of a Hall thruster is the dependence of its thrust on the anode mass flow rate of the working gas. In the process of experimental studies, the dependencies presented in Fig. 6 were obtained. Experimental dependencies show an almost linear dependence of the thrust on the mass flow rate of the working gas into the thruster’s anode unit. As seen in Fig. 6, the ST-40M thruster provides a thrust value in the range from 12 mN to 33 mN while changing the anode’s mass flow rate from 0.9 to 2.2 mg/s.

The dependence of thrust on the discharge voltage at fixed values of mass flow rate, presented in Fig. 7 are almost linear, which is associated with an increase in thrust due to an increase in the specific impulse of the thruster with an increase in the discharge voltage. Along with the magnitude of thrust, one of the most important parameters of an electric propulsion thruster is the magnitude of the specific impulse. The mass of the working gas, which must be on board the spacecraft to perform a specific mission, significantly depends on the value of the specific impulse. The dependence of the specific impulse of the ST-40M thruster on the discharge voltage at fixed values of the mass flow rate of the working substance is shown in Fig. 8.

As shown in Fig. 8, a change in the discharge voltage at fixed values of the mass flow rate of the working gas through the anode unit of the thruster leads to an almost linear change in the value of the specific impulse. This makes it possible to obtain a given value of the specific impulse of the thruster by setting the corresponding value of the discharge voltage. As shown in Fig. 8, the value of the specific impulse of the ST-40M thruster lies in the range of 1200 - 1850 s.

The conducted investigation has shown a rather high efficiency of the ST-40M Hall thruster operating with a lanthanum hexaboride cathode. The dependences of the thruster
efficiency with a change in the discharge voltage of 250 – 400 V and a discharge power of 225 – 575 W at fixed values of the anode mass flow rate of the working gas and the discharge voltage are shown in Fig. 9 - 10. As can be seen from the presented figures, the maximum anode efficiency of the ST-40 thruster reaches 48 – 52% at a discharge voltage exceeding 300 V and a discharge power in the range of 400 – 525 W.

Based on the analysis of the experimental data presented in Figs. 5 – 10, some optimal parameters of the ST-40 thruster operating with a hexaboride cathode were obtained in the discharge voltage range of 250 – 400 V and the working gas mass flow rate of 1.6 – 1.8 mg/s, which are presented in Table 1.

The research results presented in Fig. 5 – 10, allow to choose the amount of power consumption and the working gas mass flow rate, at which the Hall thruster will provide the required values of the thrust and specific impulse while maintaining the maximum efficiency of the thruster operating, which will provide optimal modes of its operation for a specific space mission.

Figure 9 – Dependence of the ST-40M efficiency on discharge voltage

In the course of experimental investigation of modified ST-40M thruster with a lanthanum hexaboride cathode, the discharge current was minimized while maintaining maximum thrust by changing the magnitude of the currents supplied to the internal and external coils of the electromagnet. In the process of adjusting the coil currents in the process of minimizing the discharge current, under certain conditions, significant fluctuations in the discharge current occurred, which led to a significant decrease in thrust and efficiency of the thruster. To determine the conditions for the occurrence of oscillations of the discharge current and ways to eliminate them, it is necessary to conduct additional studies. In general, it can be stated that fluctuations in the discharge current can be eliminated quite easily by adjusting the currents of the coils of the motor electromagnets. A sufficiently small change in the coil currents leads to a change in the nature of the oscillations, up to their complete elimination. When forming the requirements for the algorithms of the PPU operation of the propulsion system, it is necessary to take into account the need and possibility of adjusting the electromagnet currents during the operation of the propulsion system.

Figure 10 – Dependence of the ST-40M efficiency on the discharge power
### Table 1 – The main parameters of modified ST-40 thruster

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**Scientific novelty**

1. Laboratory tests of the ST-40M Hall thruster with a lanthanum hexaboride cathode confirmed its performance in the input power range of 300 – 550 W when using a stabilized voltage source as a discharge source.

2. The cyclogram for starting the lanthanum hexaboride hollow cathode with heater and modified ST-40M thruster as a whole was experimentally obtained, which provides a guaranteed start of the thruster.

3. The conducted studies made it possible to determine the Hall thruster parameters that can be recommended for various space missions, as well as for the preparation of technical specifications for the development of on-board power supplies for the engine and the propulsion unit control unit.

**Conclusions**

1. For modified ST-40M Hall thruster operating with a lanthanum hexaboride hollow cathode, in the course of experimental investigation in the discharge voltage range of 225 – 400 V, the main mass flow rate of the working substance is 0.9 – 2.2 mg/s and the mass flow rate to the cathode is 0.15 mg/s, stable start algorithms and stable operation...
modes were determined. The thruster at the same time provided a thrust value of 12 – 33 mN, a specific impulse of 1200 – 1850 s and an efficiency of 40 – 50%.

2. The experimental current-voltage characteristics of the thruster, the dependence of thrust, specific impulse and efficiency on the discharge voltage and the main mass flow rate of the working substance were obtained when using an adjustable voltage source as a power source for the discharge.

3. During the operation of the ST-40M thruster in the discharge power range of 300 – 550 W, the temperature at the engine control points at the maximum power consumption did not exceed 270°C, which confirmed the possibility of the thruster operating in the indicated power consumption range. The obtained thruster parameters significantly exceed the parameters obtained with a power consumption of 250 – 300 W.

4. In the course of the research carried out, significant oscillations in the discharge current occurred in some thruster operating modes, which were easily eliminated by changing the currents flowing through the internal and external coils of the thruster electromagnet.

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