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HALL-EFFECT THRUSTER ST-25 WITH PERMANENT MAGNET

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Abstract: Results of development and experimental tests of Hall-effect Thruster ST-25 are presented. This thruster is intended for application on small space vehicles. With the purpose of decrease of input electric power in the magnetic system of the thruster a permanent magnet is applied. The permanent magnet is located at the base of the central magnetic core. The permanent magnet provides most of the magnetic induction in the accelerating channel of the thruster, while the side magnets provide precise magnetic field adjustment. Laboratory testing of the ST-25 thruster were realized with application of the preheated hollow cathode which is operated in auto mode at the discharge current 0.5 … 0.9 A. In the process of developing the thruster, its laboratory tests were carried out with a laboratory prototype of the Xenon system for storing and supplying a working substance. The laboratory supply system provided the supply of the working gas to the anode unit 0.65 ... 0.90 mg /s and 0.07 ... 0.10 mg / s to the hollow cathode. The characteristics and parameters of the thruster were obtained using a discharge power supply that has the properties of a voltage source and a power source. The discharge power supply is the part of the flight prototype of the power processing unit. Laboratory tests have confirmed the rightness of the technical decisions stopped up in the structure of the thruster. Methodology of the thruster ST-25 start at the use of preheated cathode and flying prototype of the discharge power supply were improved. Possibility of application of such type of Hall Thrusters on space vehicles with the size of on-board electric power of that is limited to the size 200 - 300 W were confirmed.

Key words: HALL-EFFECT THRUSTER, MAGNETIC SYSTEM OF HALL THRUSTER, PERMANENT MAGNET, LABORATORY TESTS OF THE HALL THRUSTER, FLYING PROTOTYPE OF THE ELECTRIC POWER SUPPLIES, DISCHARGE VOLTAGE STABILIZATION, DISCHARGE POWER STAILIZATION, PARAMETERS OF THE HALL-EFFECT THRUSTER.

ХОЛЛОВСКИЙ ДВИГАТЕЛЬ ST-25 С ПОСТОЯННЫМ МАГНИТОМ

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Аннотация: Приведены результаты разработки и экспериментальных испытаний Холловского двигателя ST-25, предназначенного для применения на малых космических аппаратах. С целью снижения потребляемой двигателем электрической мощности в магнитной системе двигателя наряду с электромагнитом применен постоянный магнит. Постоянный магнит расположен у основания центрального магнитопровода. Постоянный магнит обеспечивает большую часть индукции магнитного поля в ускорительном канале двигателя, а боковые магниты обеспечивают точную регулировку магнитного поля. Лабораторные испытания двигателя проводились с накальным катодом, который работает в авторежиме при токе разряда 0.5 … 0.9А. В процессе отработки двигателя его лабораторные испытания проводились с лабораторным прототипом ксеноновой системы хранения и подачи рабочего вещества. Лабораторная система подачи обеспечила подачу рабочего газа (ксенона) в анодный блок 0.65 … 0.90 мг\с и 0.07 … 0.10 мг\с в полый катод. Характеристики и параметры двигателя получены при использовании источника электропитания разряда, обладающего свойствами источника напряжения и источника мощности. Источник электропитания разряда входит в состав летного прототипа системы преобразования энергии. Результаты лабораторных испытаний двигателя ST-25 подтвердили правильность технических решений, заложенных в конструкцию двигателя. Была отработана методика

запуска двигателя ST-25 при использовании накального катода и летного прототипа источников электропитания. Подтверждена возможность применения такого типа Холловских двигателей на космических аппаратах, бортовая электрическая мощность которых ограничена величиной 200 – 300 Вт.
Ключевые слова: ХОЛЛОВСКИЙ ДВИГАТЕЛЬ, МАГНИТНАЯ СИСТЕМА ХОЛЛОВСКОГО ДВИГАТЕЛЯ, ПОСТОЯННЫЙ МАГНИТ, ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ ХОЛЛОВСКОГО ДВИГАТЕЛЯ, ЛЕТНЫЙ ПРОТОТИП ИСТОЧНИКОВ ЭЛЕКТРОПИТАНИЯ ДВИГАТЕЛЯ, СТАБИЛИЗАЦИЯ НАПРЯЖЕНИЯ РАЗРЯДА, СТАБИЛИЗАЦИЯ МОЩНОСТИ РАЗРЯДА, ПАРАМЕТРЫ ХОЛЛОВСКОГО ДВИГАТЕЛЯ.

ХОЛЛОВСЬКИЙ ДВИГУН ST-25 З ПОСТІЙНИМ МАГНІТОМ

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Анотація: Наведено результати розробки та експериментальних випробувань Холловського двигуна ST-25, призначеного для використання на малих космічних апаратах. З метою зниження електричної потужності, що споживається, в магнітній системи двигуна використаний постійний магніт. Постійний магніт розташований біля основи центрального магнітопроводу. Постійний магніт забезпечує більшу частину індукції магнітного поля в прискорюючому каналі двигуна, а бокові магніти забезпечують точне регулювання магнітного поля. Лабораторні випробування двигуна проводились з накальним катодом, який працює в авторежимі при струмі розряду 0.5 … 0.9 А. В процесі відпрацювання двигуна його лабораторні випробування проводились з лабораторним прототипом ксенонової системи зберігання та подачі робочої речовини. Лабораторна система подачі забезпечила подачу робочої речовини (ксенону) в анодний блок 0.65 … 0.90 мг/с і 0.07 … 0.10 мг/с в полий катод. Характеристики та параметри двигуна отримані з використанням джерела електроживлення розряду, який иає властивості джерела напруги та джерела потужності. Джерело електроживлення розряду входить до складу льотного прототипу системи перетворення енергії. Результати лабораторних випробувань двигуна ST-25 підтвердили правильність технічних рішень, які було закладено в конструкцію двигуна. Була відпрацьована методика запуску двигуна ST-25 при використанні накального катоду та льотного прототипу джерел електроживлення. Підтверджена можливість використання такого типу Холловський двигунів на космічних апаратах, бортова електрична потужність яких обмежена величиною 200 – 300 Вт.
Ключові слова: ХОЛЛОВСЬКИЙ ДВИГУН, МАГНІТНА СИСТЕМА ХОЛЛОВСЬКОГО ДВИГУНА, ПОСТІЙНИЙ МАГНІТ, ЛАБОРАТОРНІ ВИПРОБУВАННЯ ХОЛЛОВСЬКОГО ДВИГУНА, ЛЬОТНИЙ ПРОТОТИП ДЖЕРЕЛ ЕЛЕКТРОЖИВЛЕННЯ ДВИГУНА, СТАБІЛІЗАЦІЯ НАПРУГИ РОЗРЯДУ, СТАБІЛІЗАЦІЯ ПОТУЖНОСТІ РОЗРЯДУ, ПАРАМЕТРИ ХОЛЛОВСЬКОГО ДВИГУНА.

Introduction

Electric propulsion thrusters (EPT) are widely used on spacecraft vehicles (SC) for solving the problems of orientation and stabilization, maintaining and changing the parameters of the orbit, SC deorbiting after the end of the spacecraft mission.

The most widely used EPTs are the M-70 and SPT-100 thrusters, developed by EDO “Fakel” (Kaliningrad, Russia) [1]. These thrusters have a power consumption of 660 - 1200 W and are used on spacecraft that have a sufficient amount of electrical power on board.

At the same time, the current stage of space technology development is characterized by a significant decrease in the spacecraft mass, as a result of which the level of electrical energy on board the spacecraft does not exceed 400 - 500 W, and no more than 200 - 300 W of electrical power can be allocated for electric propulsion thrusters. [2].

Formulation of the research problem

Design of the electric propulsion thruster with power consumption in the range 200 – 300 W. Laboratory testing of designed thruster at two regimes of the discharge power supply operating a) with discharge voltage stabilization; b) with discharge power stabilization. To determine the main static characteristics of the thruster for both regimes of the discharge power supply operation. As results of the thruster laboratory testing to determine the optimal regimes of the electric propulsion thruster operation.

Solution of the research problem

For solution of the electric propulsion thruster design with small power consumption for small spacecraft, one of the Hall-effect thruster variant was chosen. That is Hall-effect thruster with the insulation-accelerating channel, in which axial electric and radial magnetic fields were realized – ST-25.

Specific of the ST-25 structure is using the permanent magnet in central core for decreasing electrical power for creation the radial magnet field in the thruster acceleration cannel [3]. The permanent magnet is manufactured from material SmCo, point Curie of which is in the range 810 … 900°C, that is why such magnet can be used at the working temperature about 350°C. As outer electromagnets four traditional electromagnet are used. The stable current for these electromagnets is used from separate power supply. General view of the ST-25 thruster with the hollow cathode is presented on fig.1.

Figure 1 – General view of ST-25 Hall thruster (with cathode)

ST-25 thruster consists of annular discharge channel and magnetic system which create the radial magnet field. Working substance (Xenon) is feed into anode which is located at the acceleration channel bottom. An arc discharge is created between anode and outer hollow cathode in the acceleration channel. Ions, which are born as result of arc discharge in acceleration channel, are accelerated by axial electrical field. The flow of accelerated ions is neutralized by electrons which are moved from hollow cathode. In this way behind the thruster cut the neutral atoms flow of working substance is forming which determined the value of the thrust.

For the ST-25 thruster the preheated hollow cathode was designed and developed. It insures keeping arc discharge in the thruster acceleration channel and neutralization of the ion beam. The hollow cathode working current which keeps auto regime operation is 0,6…1,0 A, the value of the hollow cathode mass flow rate is in the range 0.06…0.10 mg/sec.

Laboratory testing of the thruster

ST-25 thruster laboratory testing was carried out in the testing laboratory of SETS (Dnipro, Ukraine) with using the experimental facility, consists of the vacuum chamber, the laboratory storage and feed system, flight prototype of the power-processing unit and laboratory instrumentation rack. General view of the experimental facility is presented on fig.2.

Figure 2 – General view of the experimental facility for ST-25 testing

The vacuum chamber was equipped by turbomolecular pump, which provides the vacuum $1{\cdot}10^{-6}$ Tor at absence of the working gas mass flow rate and value $2{\cdot}10^{-4}$ Tor at the maximal mass flow rates into anode and hollow cathode. Inside of vacuum chamber the devise for measurement of the thrust level is located. This devise can be used for measurement of the thrust in the range 0.0 … 20.0 mN. The error of the thrust measure is about ± 5% from maximal value.

Laboratory Xenon storage and feed system (XFS), which was used for feeding the working gas into anode unit and hollow cathode. It consists of the tank with Xenon, the reducer, manometer and devises of control and measurement the mass flow rate (fig. 2). Referenced values the mass flow rates into anode unit and hollow cathode are determined by devises F-201CV Bronkhorst Company.

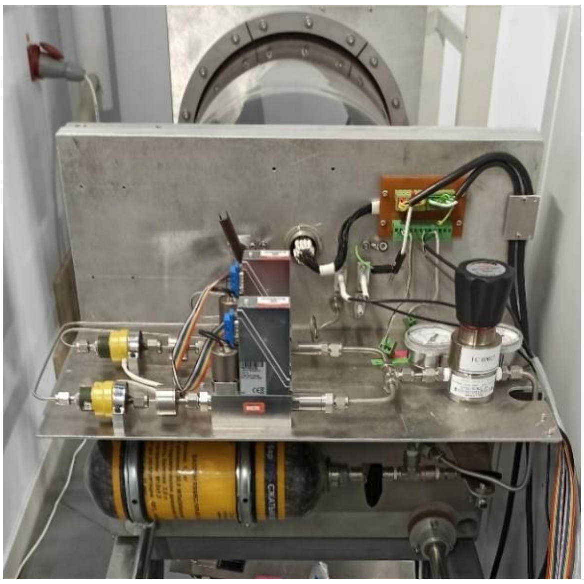

Figure 3 – Laboratory storage and feed system for ST-25 testing

Flight prototype of the power-processing unit for ST-25 thruster (PPU) includes the power supplies: discharge, electromagnet, heater and keeper of cathode and supplies insured the storage and feed system operation. Electrical scheme connection of ST-25 thruster to power processing unit and XFS is presented on fig. 4.

On this figure such notations are used:

Ud – discharge voltage;
Iem – electromagnet current;
Ih – current of the cathode heater;
Uk – voltage of the cathode keeper;
m1 – mass flow rate into anode unit;
m2 – mass flow rate into hollow cathode.

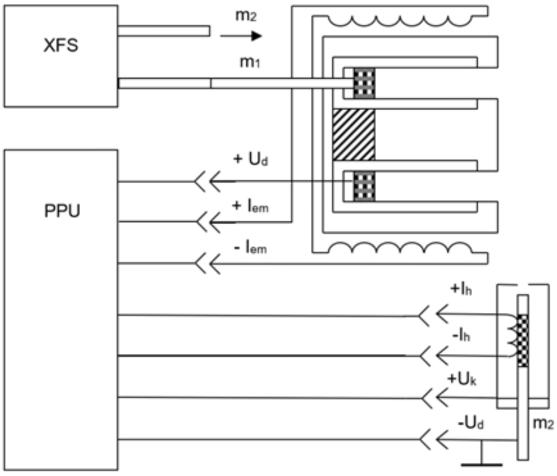

Figure 4 – Scheme connection of ST-25 thruster to power-processing unit

Laboratory testing of the thruster was carried out by two stage. At the first stage ST-25 thruster was tested with the discharge power supply operating in regime discharge voltage stabilization; electromagnet current supply and voltage supply of the keeper hollow cathode.

During the first stage of testing following characteristics of the thruster were determined: dependency the thrust from discharge voltage and discharge power at the fixed levels of the anode mass flow rate; the thrust from anode mass flow rate at fixed levels discharge voltage and also the value of specific impulse from discharge voltage.

Discharge voltage was changed in the range 150 … 250 V; mass flow rate into anode unit was changed in the range 0.5 … 0.9 mg/s; mass flow rate into hollow cathode was kept at level 0.07 mg/s: discharge power in anode unit was changed in the range 70 … 270 W.

The graphs of the obtained characteristics of the ST-25 thruster at using discharge power supply with voltage stabilizing on Fig. 5 – Fig. 8 are presented.

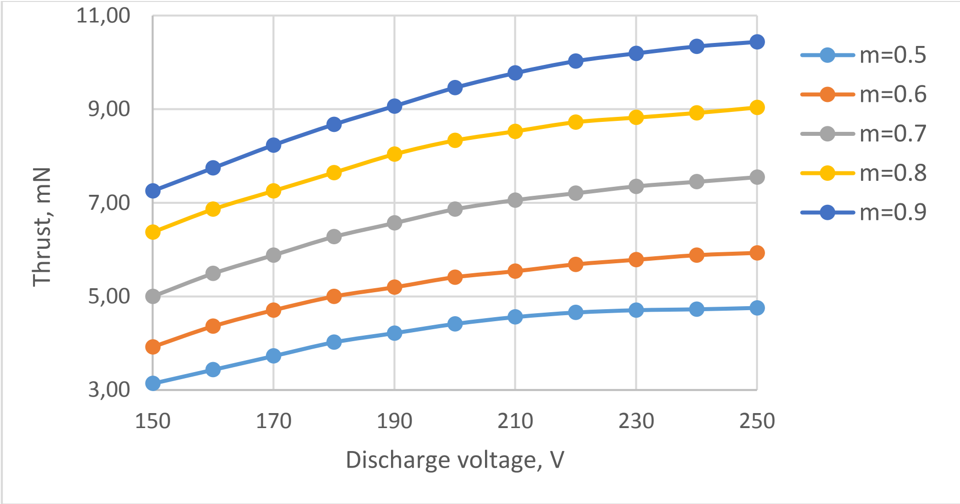

Figure 5 – Dependence of the thrust from discharge voltage

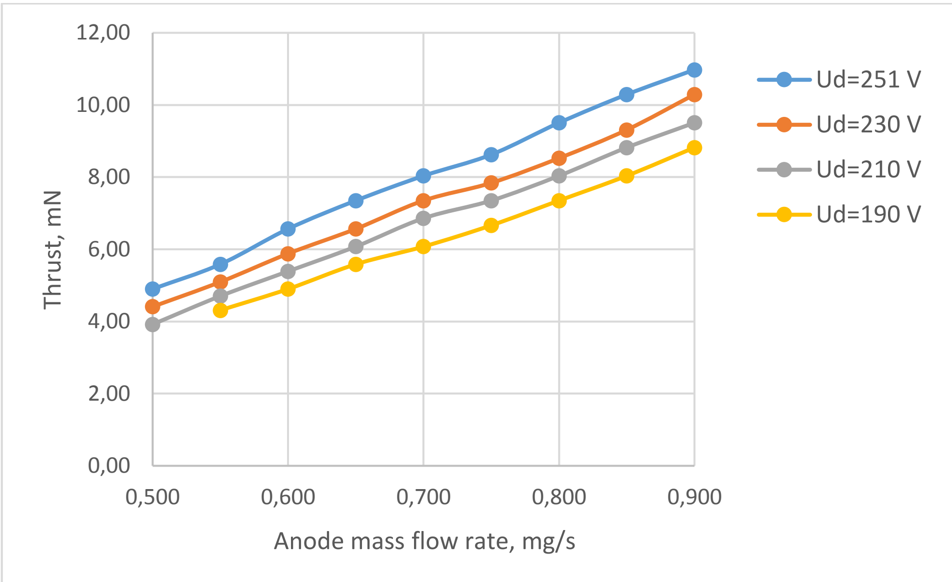

Figure 6 – Dependence of the thrust from mass flow rate into anode unit

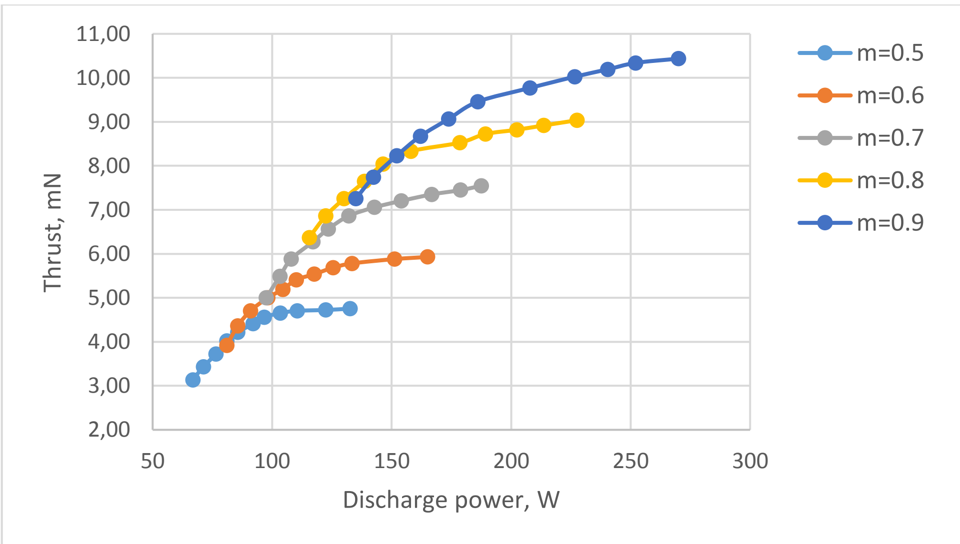

Figure 7 – Dependence of the thrust from discharge power

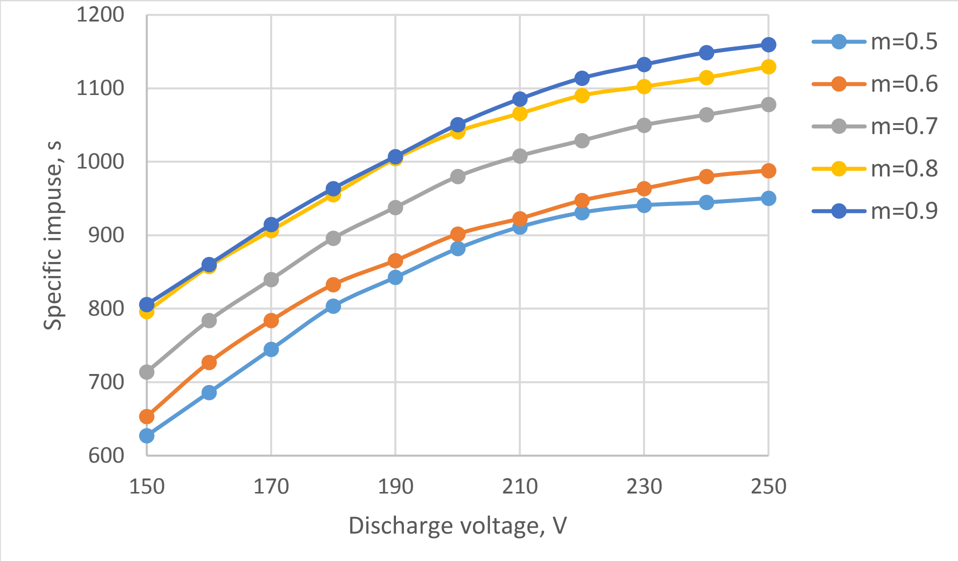

Figure 8 – Dependence of the specific impulse from discharge voltage

It's known [4], the Hall-effect thruster parameters and characteristics which are obtained with using the discharge voltage supply can be strongly differenced from parameters and characteristics obtained with using the discharge power supply. That is why during the second stage of the ST-25 testing flight prototype the discharge power supply was used. This discharge power supply is as component of the PPU flight prototype and insures the discharge power stabilizing. General view of the discharge power supply which was used during the second stage the thruster testing is presented on fig. 9. General technical parameters of this discharge power supply is presented in Table 1.

Table 1 – Parameters of the discharge power supply flight prototype

Parameters	Value
Input voltage, V	20…36
Maximal input power, W	400
Maximal discharge power, W	300
The range discharge voltage, V	50…400
Regimes of stabilizing	Voltage/ Power
Efficiency, %	> 95
Mass, kg	3.5
Dimensions, мм	220x150x75

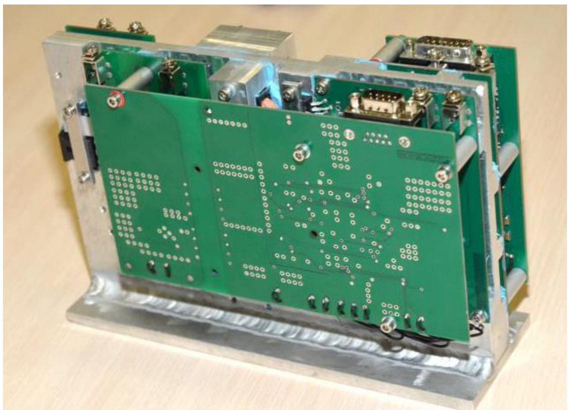

Figure 9 – The discharge power supply flight prototype general view

In results of the ST-25 thruster testing using discharge power supply insured discharge power stabilizing dependences the thrust from anode mass flow rate and discharge power; the specific impulse and efficiency values from disgorge power are obtained. The graphs of correspondent experimental dependencies are presented on Fig. 10 – Fig. 13.

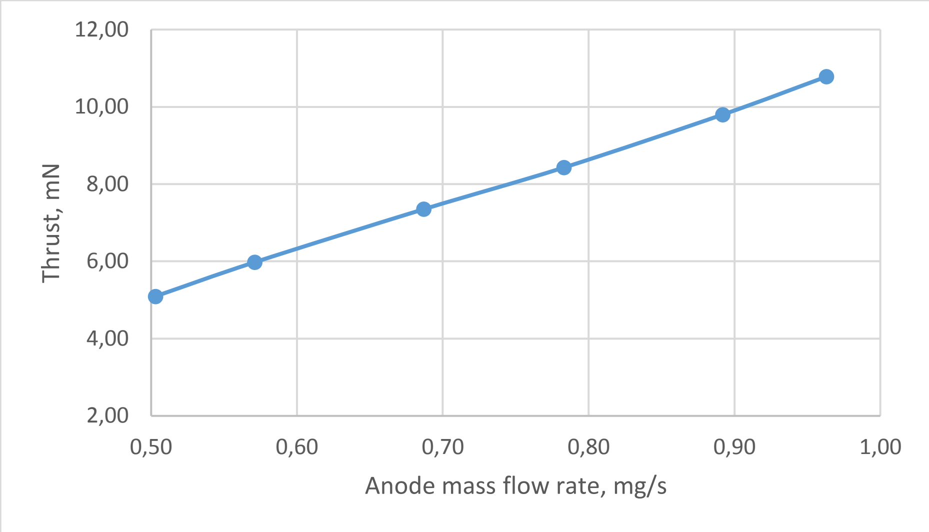

Figure 10 – Dependence of the ST-25 thrust from anode mass flow rate at the discharge power stabilizing

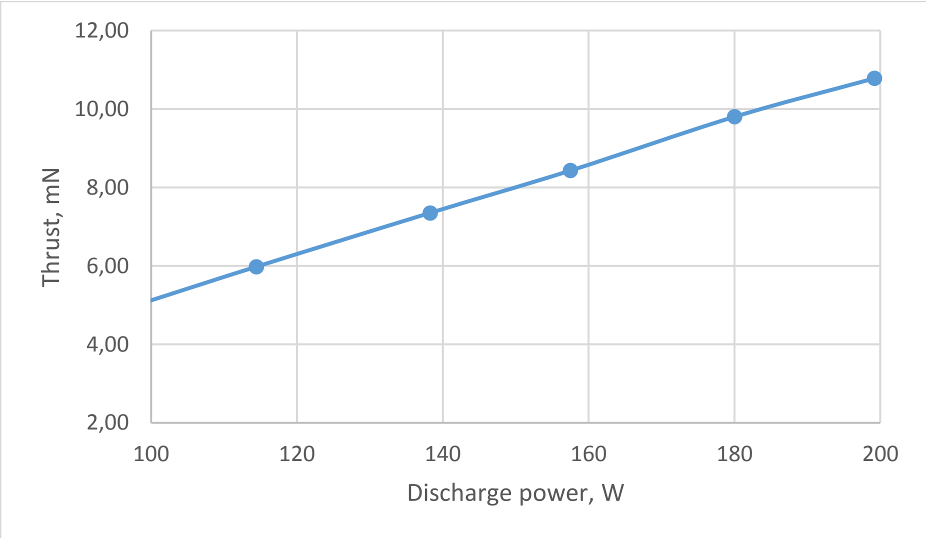

Figure 11 – The dependence of the ST-25 thrust from the discharge power

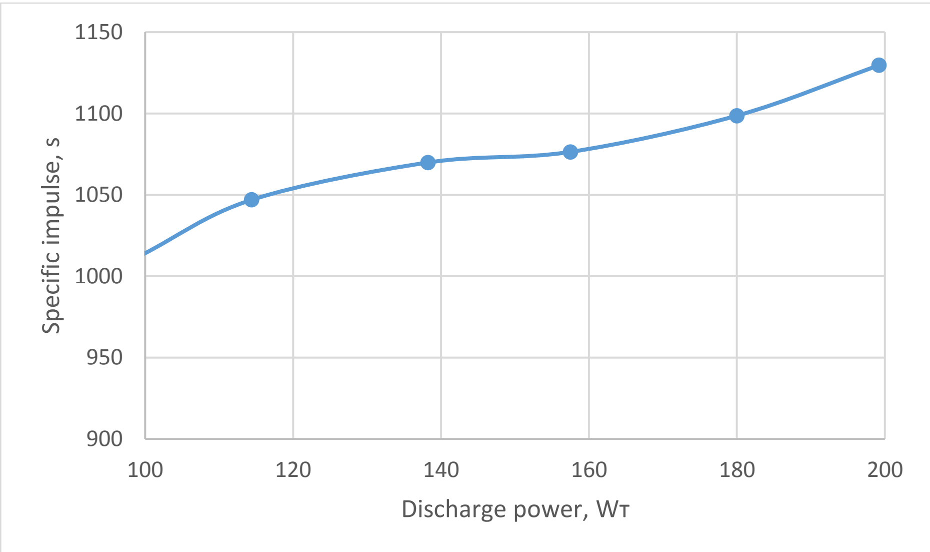

Figure 12 – The dependence of the ST-25 specific impulse from discharge power

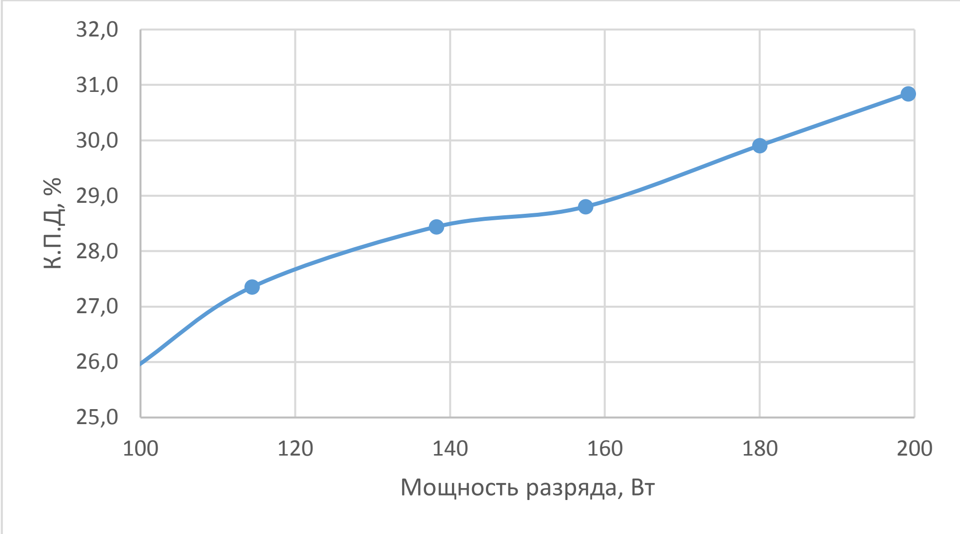

Figure 13 – The dependence of the ST-25 efficiency from discharge power

In frame of the ST-25 laboratory testing alongside with the static characteristics determining the cyclogram of the thruster starting was developed. Typical cyclogram of the thruster starting is presented on Fig. 14.

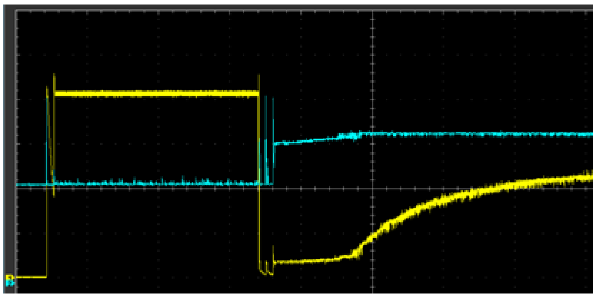

Figure 14 – Typical cyclorama of the ST-25 starting

As a result of the Hall thruster ST-25 with a permanent magnet as part of the magnetic system design and laboratory investigation, the main technical parameters were obtained and given in table. 2.

Laboratory testing of the thruster have shown that when it is operating with a power consumption of 150 - 200 W, the consumption of electrical energy for the operation of external electromagnets does not exceed 10 W and are used only for precision regulation of the magnetic field induction in the accelerating channel of the thruster. The main role in creating the required value of the induction of the radial magnetic field is played by the permanent magnet.

Таблица 2 – Параметры двигателя ST-25

Parameters	Value
Input power, W	150 …200
Discharge voltage, V	200 …260
Electromagnet power, W	< 10
Power of cathode heater, W	< 50
Anode mass flow rate, mg/s	0.65…0.90
Cathode mass flow rate, mg/s	0.07 … 0.10
Thrust, mN	7 …11
Specific impulse, s	< 1200
Thrust efficiency, %	< 30
Cost of the thrust, W/mN	19…21
Mass of the thruster, kg	0.75
Dimensions (without cathode), mm	79x79x79.5
Lifetime (estimation), hr.	3000

Scientific novelty

1. The conducted research of the Hall thruster ST-25 confirmed the effectiveness of using a permanent magnet as part of the magnetic system, as a result of which it was possible to significantly reduce the power consumption of the thruster.

2. The optimal parameters of the Hall thruster ST-25 have been obtained, which correspond to the parameters of the thrusters developed by the world's leading companies.

3. It has been proved that there is a direct dependence of the ST-25 thrust value on the

mass flow rate of the working substance through the engine anode. In this case, the magnitude of the engine thrust does not depend on the change in the flow rate of the working substance through the hollow cathode.

4. For the first time, experimental studies of the Hall thruster were carried out, which made it possible to compare its parameters obtained using voltage stabilization and stabilization of the discharge power.

5. For the first time, the technique of starting the Hall thruster using a hollow filament cathode and stabilization of the discharge power was developed. The resulting method of starting the engine is used in the propulsion system control algorithms.

Conclusions

As a result of the research carried out by the Hall motor with a permanent magnet and a filament cathode ST-25, developed by Space Electric Thruster Systems, all the tasks were completed and the possibility of using this type of engine on spacecraft was confirmed, the onboard power of which is limited to 200 - 300 W.

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