

ST-25 HALL-EFFECT THRUSTER WITH PERMANENT MAGNET

D.K. Voronovsky^{1,2}, S.M. Kulagin¹, V.V. Maslov¹, O.M. Petrenko^{1,2}, S.V. Tolok^{1,2}

¹*Space Electric Thruster Systems, Gagarin Ave. 115, Dnipro, 49050, Ukraine*

²*Dniprovsky National University named Oles Honchar, Gagarin Ave. 72, Dnipro, 49050, Ukraine*

Abstract: Results of development and experimental tests of ST-25 Hall-effect Thruster 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.

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, deorbiting the SC after the end of the 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 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 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 insulator 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 channel [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. Structure scheme of the ST-25 thruster (without hollow cathode) is presented on Fig. 1.

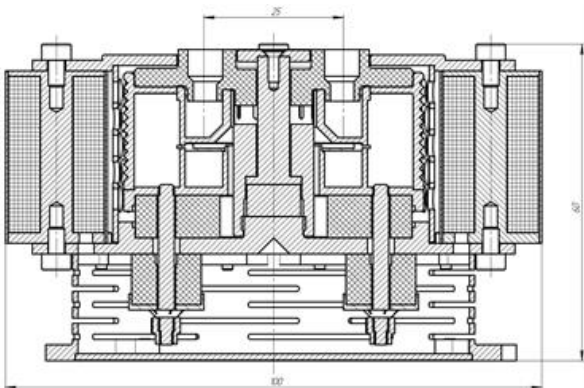


Figure 1 – Structure scheme of ST-25 Hall-effect thruster (without cathode)

ST-25 thruster consists of annular discharge channel and magnetic system which create the radial magnet field. Working substance (Xenon) is fed into Anod which is located at the acceleration channel bottom. An arc discharge is created between Anod 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, laboratory storage and feed system, flight prototype 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 is 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 $\pm 5\%$ 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

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

On this figure such notations are used:
 U_d – discharge voltage;

I_{em} – electromagnet current;
 I_h – current of the cathode heater;
 U_k – voltage of the cathode keeper;
 m_1 – mass flow rate into anode unit;
 m_2 – mass flow rate into hollow cathode.

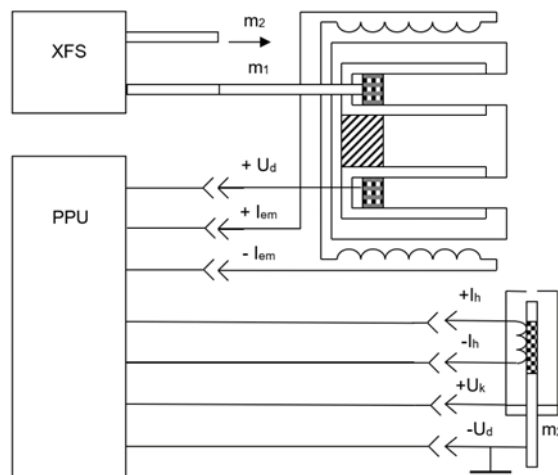


Figure 4 – Scheme connection ST-25 thruster to power processing unit

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 are presented on Fig. 5 – Fig. 8

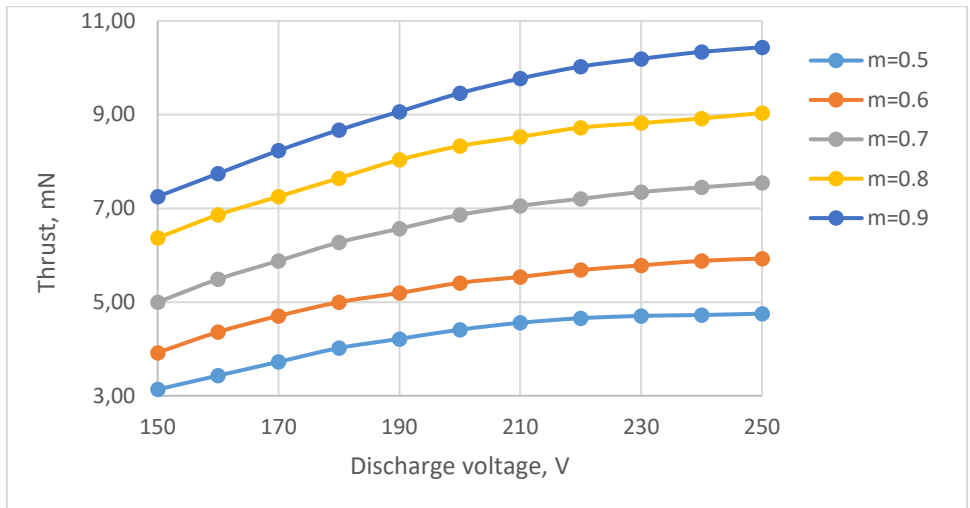


Figure 5 – Dependence of the thrust from discharge voltage

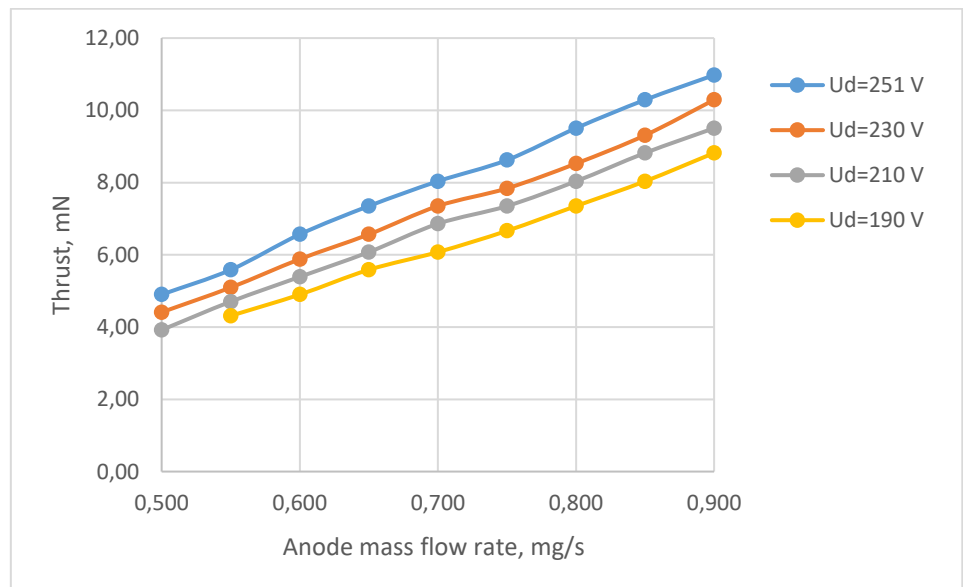


Figure 6 – Dependence of the thrust from mass flow rate into anode unit

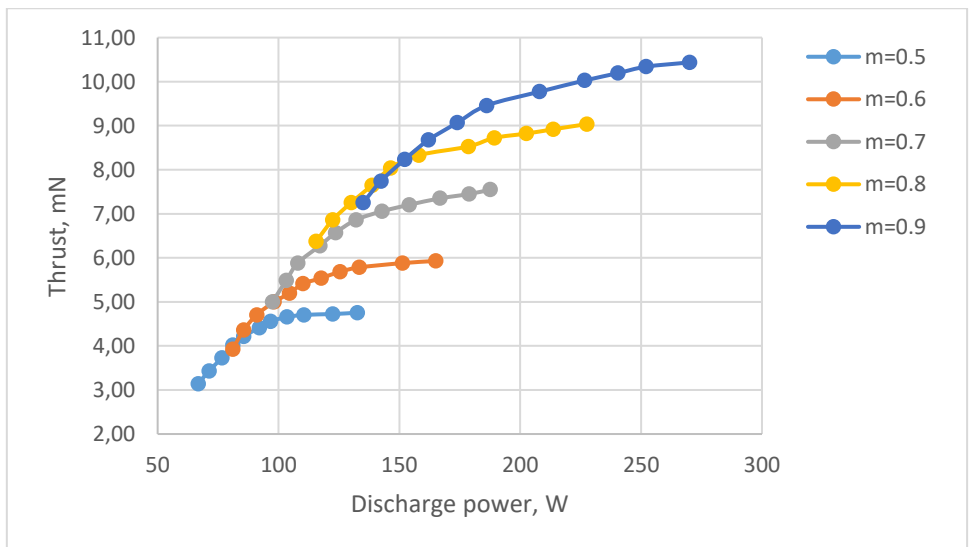


Figure 7 – Dependence of the thrust from discharge power

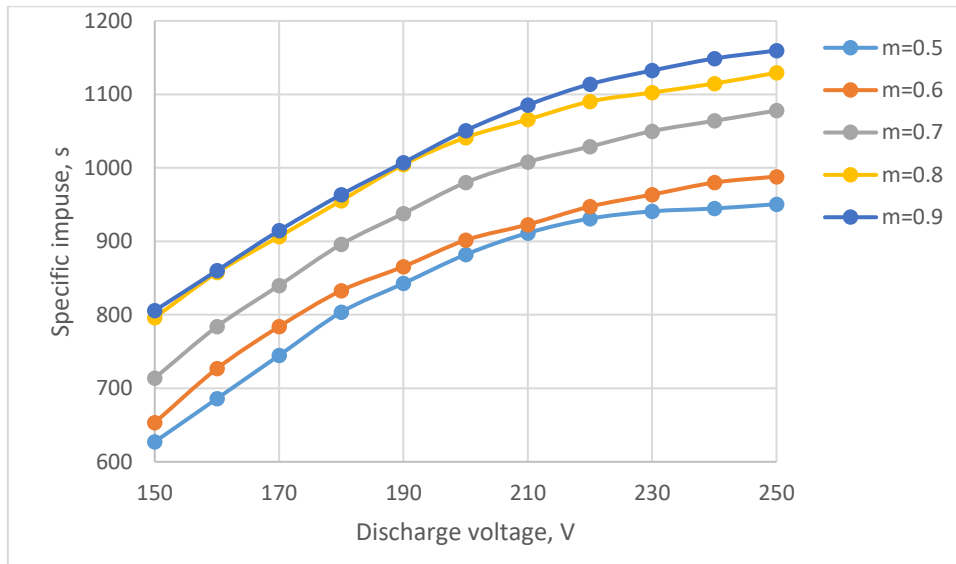


Figure 8 – Dependence of the specific impulse from discharge voltage

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, MM	220x150x75

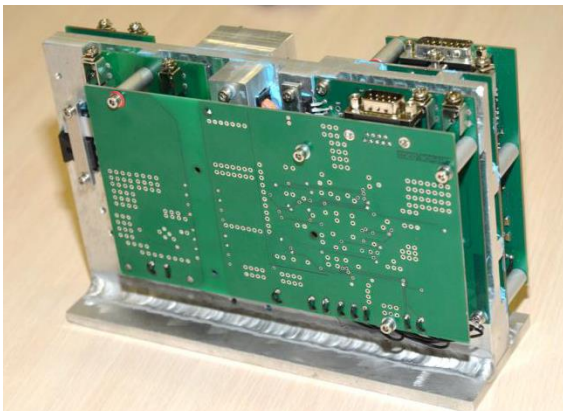


Figure 9 – The discharge power supply flight prototype general view

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

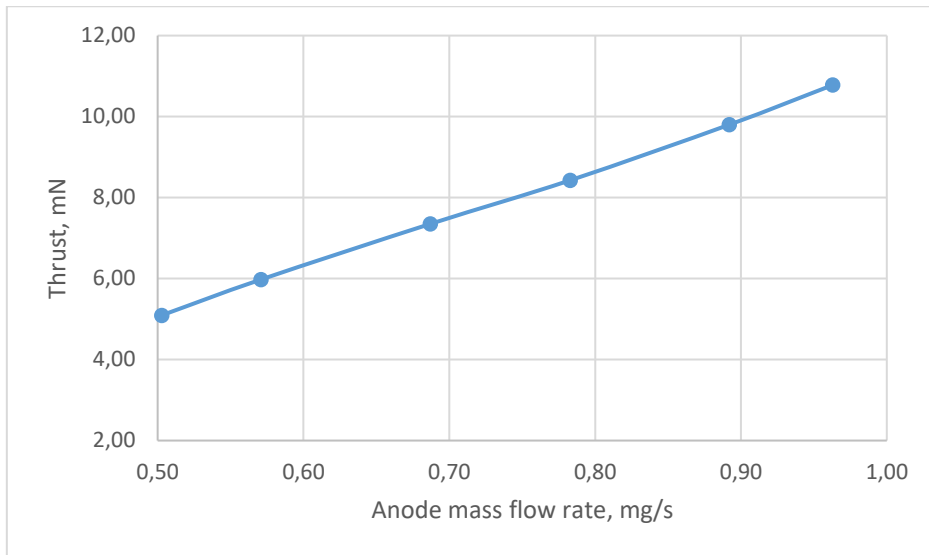


Figure 10 – Dependence of the ST-25 thrust from anode mass flow rate at the discharge power stabilizing

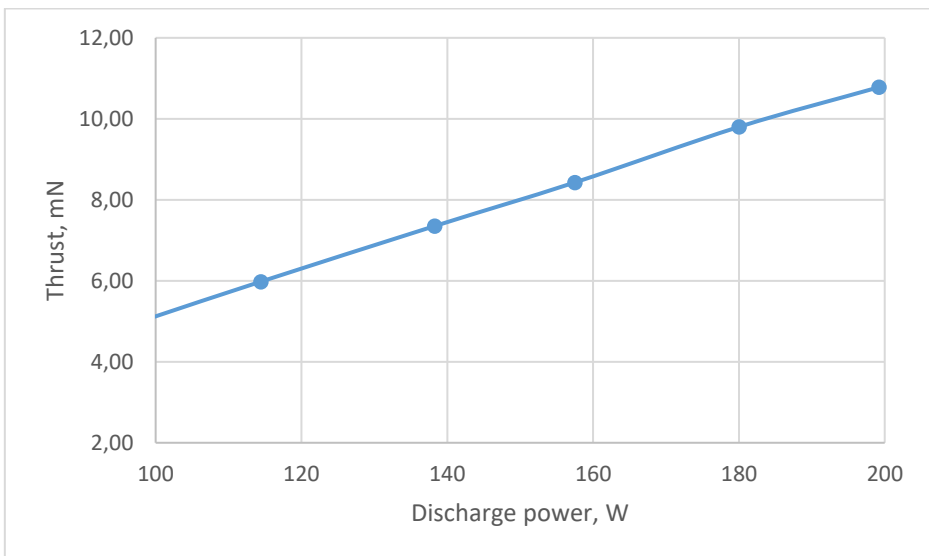


Figure 11 – The dependence of the ST-25 thrust from the discharge power

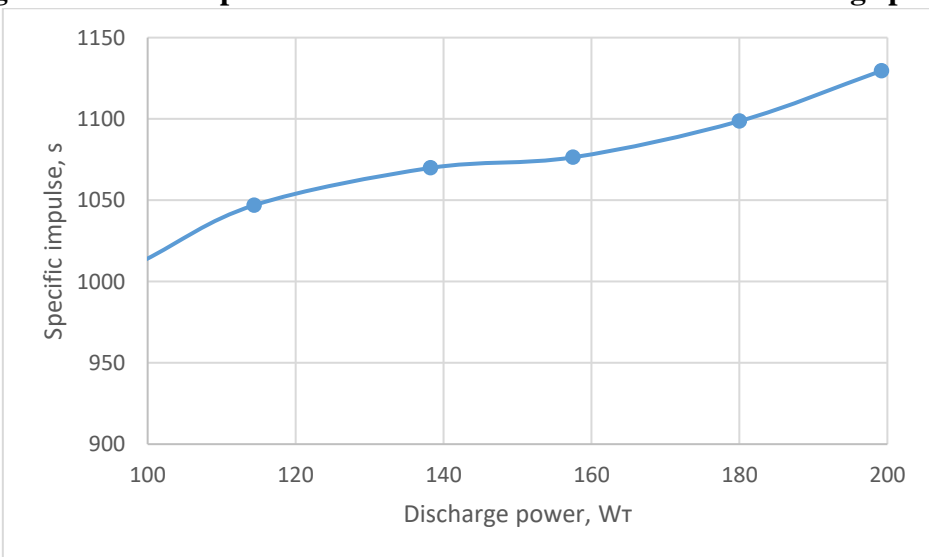


Figure 12 – The dependence of the ST-25 specific impulse from discharge power

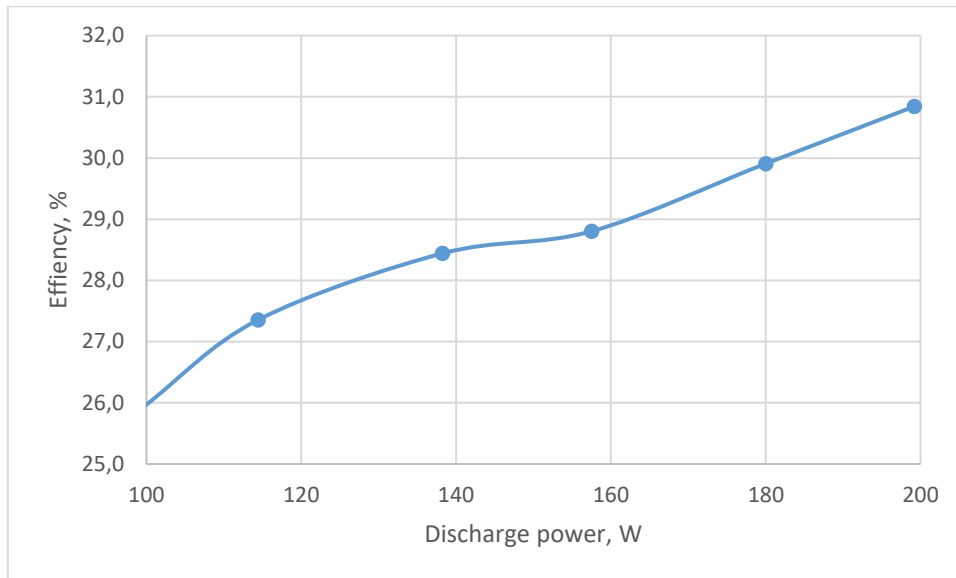


Figure 13 – The dependence of the ST-25 efficiency from discharge power

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.

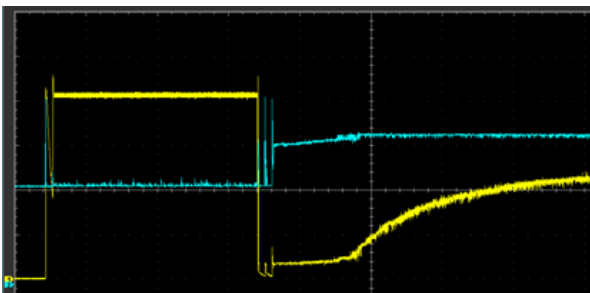


Figure 14 – Typical cyclogram of the ST-25 starting

Conclusions:

1. In results of this work Hall-effect thruster with permanent magnet was designed, manufactured and tested. The main parameters of the designed thruster are presented in Table 2, general view is presented on Fig. 15.

2. The laboratory testing improved efficiency of application in magnetic system

structure the permanent magnet. In result the level of electric power for radial magnetic field creation was significantly decreased.

3. Experimental characteristics and parameters of the ST-25 thruster were obtained with using the laboratory power supplies which have proprieties of flight prototypes.

4. The methodic of the thruster with preheated cathode starting was designed and developed.

5. As result of ST-25 thruster testing it was improved the possibility of application

6. such type of the thruster onboard spacecraft in which primary power less than 300 ... 500 W.



Figure 14 – General view of the ST-25 thruster with hollow cathode

Table 2 – Characteristics of ST-25 thruster

Parameters	Value
Input power, W	150 ...200
Discharge voltage, V	200 ...260
Electromagnet electric 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 (with one cathode), kg	0.75
Dimensions (without cathode), mm	79x79x79.5
Lifetime (estimation), hr.	3000

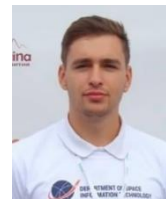
References:

1. Архипов А.С. Стационарные плазменные двигатели Морозова / А.С. Архипов, В.П. Ким, Е.К. Сидоренко. – М.: МАИ, 2012. – 292 с.
2. Гопанчук В.В., Потапенко М.Ю. Электрореактивные двигатели для малых космических аппаратов / В.В. Гопанчук, М.Ю. Потапенко. Вестник Балтийского федерального университета им. И. Канта. 2012. Вып. 4. С. 60 – 67.
3. Rossi A. Parametric optimization of a Hall Effect Thruster magnetic circuit / A. Rossi, F. Messine, C. Henaux, S. Sanogo. Processing of 34th International Electric Propulsion Conference. IEPC-2015-40, Hyogo-Kobe, Japan, 2015.
4. Petrenko O. Results of Research of Steady Work Models of Stationary Plasma Thrusters. Processing of the 47th International Astronautical Congress, IAF-96-S.3.03, Beijing, China, 1996.
5. Petrenko O. The effect of power supply output characteristics on the operation of the SPT-100 Thruster / O. Petrenko, Hamley, J.A., Sankovic, J.M. Processing of the 24th International Electric Propulsion Conference, IEPC-95-241, Moscow, Russia, September 19-23, 1995.

6. Bugrova A.I., Desiatskov A.V., Kaufman H.R., et al. Design and experimental investigation of a small closed drift thruster // Proc. of the 27th International Electronic Propulsion Conference. 2001. IEPC-2001-344.
7. Polk J. Electric propulsion in the USA // Proc. of the 30th International Electronic Propulsion Conference (Florence, Italy, 2007). IEPC-2007-368.

Entered the editorial board 30.10.2020.

Information about authors



Voronovsky Dmitriy Konstantinovich. Ukraine. Space Electric Thruster Systems. Dnipro. Engineer-researcher. Dniprovsky National University named Oles Honchar. Post-graduate student.

Interest sphere – design and testing Hall-effect thrusters.



Kulagin Sergey Nikolaevich. Ukraine. Space Electric Thruster Systems. Dnipro. Researcher – designer. Institute of Technical Mechanics National Academy of Science of Ukraine. Dnipro. Senior researcher,

Ph.D
Interest sphere – optimizing of working processes in Hall-effect thrusters and hollow cathodes.



Maslov Victor Vladimirovich. Украина. Space Electric Thruster Systems. Dnipro. Engineer-researcher. Interest sphere – design and testing Hall-effect thrusters.



Petrenko Olexandr Nikolaevich. Ukraine. Space Electric Thruster Systems, Dnipro. Scientific consultant. Dniprovsky National University named Oles Honchar. Professor, D.S. Interests sphere – design and testing of the electrical propulsion engine systems with Hall-effect thrusters' application.



Tolok Stanislav Victorovich. Ukraine. Space Electric Thruster Systems. Dnipro. СТО. Dniprovsky National University named Oles Honchar. Post-graduate student.

Interests sphere – design and testing of the electric propulsion engine systems.