Abstract. The results of the start sequence diagram selection and experimental tests of the ST-25 Hall thruster intended for using on small spacecraft are presented. In order to reduce the mass and dimensions of the power processing unit of the propulsion system, it is proposed to exclude the hollow cathode keeper power supply from the structure of the power processing unit. The exclusion of the keeper power supply from the power processing unit made it necessary to select the thruster start sequence diagram. Four start sequence diagrams of the ST-25 Hall thruster start-up are considered: a) using a separate high voltage power supply for the hollow cathode keeper; b) using a separate low voltage power supply for the hollow cathode keeper; c) using a discharge power supply connected to the keeper through a high-resistance resistor to the hollow cathode keeper; d) connecting the keeper of the hollow cathode to the discharge power supply through an electronic switch with the possibility of adjusting the duration of the keeper connection to the discharge power supply. The graphs of changes in the thruster’s currents and voltages for various power supply circuits of the hollow cathode keeper are presented. The results of the choice of the start sequence diagram for the Hall engine ST-25 and the experimental studies carried out have shown that the use of an electronic switch with a steep pulse front makes it possible to obtain a reliable thruster start-up when a separate power supply for the keeper is excluded from the power processing unit of the propulsion system. As a result of the work carried out, it became possible to place the power processing unit for a propulsion system based on the ST-25 thruster in a volume of 2U. The possibility of using ST-25 thruster on spacecraft, the onboard electrical power of which is limited up to 200 W were confirmed.

Key words: HALL-EFFECT THRUSTER, START SEQUENCE DIAGRAM, LABORATORY TESTS OF THE HALL THRUSTER, STRUCTURE OF POWER PROCESSING UNIT, POWER SUPPLY FOR THE HOLLOW CATHODE KEEPER.
преобразования энергии двигательной установки отдельного источника электропитания кипера. В результате проведенных работ оказалось возможным систему преобразования энергии для двигательной установки на базе двигателя ST-25 разместить в объеме 2U. Подтверждена возможность применения двигателей ST-25 на космических аппаратах, бортовая электрическая мощность которых ограничена величиной 200 Вт.

Ключевые слова: ХОЛЛОВСКИЙ ДВИГАТЕЛЬ, ЦИКЛОГРАМА ЗАПУСКА, ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ ХОЛЛОВСКОГО ДВИГАТЕЛЯ, СТРУКТУРА СИСТЕМЫ ПРЕОБРАЗОВАНИЯ ЭНЕРГИИ, ИСТОЧНИК ЭЛЕКТРОПИТАНИЯ КИПЕРА ПОЛОГО КАТОДА.

ЦИКЛОГРАМИ ЗАПУСКУ ХОЛЛОВСКОГО ДВИГУНА ST-25
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Анотація. Наведено результати вибору циклограми запуску та експериментальних випробувань Холловського двигуна ST-25, призначеного для використання на малних космічних апаратах. З метою зниження маси та габаритів системи перетворення енергії двигунної установки зі структурної схеми системи перетворення енергії запропоновано виключити джерело електророзряду кипера полого катоду. Виключення джерела електророзряду кипера зі складу системи перетворення енергії викликало необхідність здійснити вибір циклограми запуску двигуна. Розглянуто чотири циклограми запуску Холловського двигуна ST-25: а) з використанням високовольтного джерела електророзряду кипера полого катоду; б) з використанням низьковольтного джерела електророзряду кипера полого катоду; в) використанням для живлення кипера полого катоду джерела живлення розряду через високоомний резистор; г) підключення кипера полого катоду до джерела живлення розряду через електронний ключ з можливістю регулювання часу підключення кипера до джерела розряду. Наведено графіки зміни струмів та напруг двигуна для різних схем електророзряду кипера полого катоду. Результати вибору циклограми запуску Холловського двигуна ST-25 та проведені експериментальні дослідження показали, що використання електронного ключа з крутим фронтом імпульсу дозволяє забезпечити надійний запуск двигуна при виключенні зі складу системи перетворення енергії двигунної установки окремого джерела живлення кипера. В результаті проведених досліджень виявилось можливим систему перетворення енергії для двигунної установки на базі двигуна ST-25 розмістити у об'ємі 2U. Підтверджено можливість використання двигунів ST-25 на космічних апаратах, бортова електрична потужність яких обмежена величиною 200 Вт.

Ключові слова: ХОЛЛОВСЬКИЙ ДВИГУН, ЦИКЛОГРАМА ЗАПУСКА, ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ ХОЛЛОВСКОГО ДВИГАТЕЛЯ, СТРУКТУРА СИСТЕМЫ ПЕРЕТВОРЕННЯ ЭНЕРГИИ, ДЖЕРЕЛО ЕЛЕКТРОРЗЯДУ КИПЕРА ПОЛОГО КАТОДА.

Introduction
Hall-effect thrusters (HT) are widely used on spacecraft (SC) for solving various tasks: orientation and stabilization, maintaining and changing the parameters of the orbit, breaking the SC after the completion of the mission.

One of the promising HTs for small spacecraft is the ST-25 thruster. In this thruster, to reduce the power consumption for creating a radial magnetic field in the accelerating channel, a permanent magnet is used together with electromagnets [1].

Along with restrictions on the amount of power consumed by electric propulsion systems (EPS), significant restrictions are imposed on the mass-dimensional characteristics of all EPS subsystems. These limitations primarily relate to the power processing and control unit (PPU), the mass and dimensions of which depend on the composition of the power supplies that make up the PPU, as well as on their parameters.

Along with minimizing the mass and dimensions of all EPS subsystems, it is necessary to provide a reliable EPS startup algorithm. The typical PPU structure of a propulsion system with Hall-effect thruster includes the following power supplies: a discharge source, an electromagnet source, a hollow cathode preheat source, and a keeper power supply.
The sequence of the start-up of the Hall-effect thruster sets the sequence for supplying the supply voltages and currents to the EPS subsystems, as well as the supply of the working substance flow rates to the anode-gas distributor and the hollow cathode of the thruster.

The choice of the cyclorama for starting the Hall-effect thruster is not a trivial task and requires research, including experimental ones.

**Formulation of the research problem**

To develop a sequence diagram of the ST-25 Hall-effect thruster start, which ensures reliable thruster start using a minimum number of power supplies included in the PPU.

Consider the possibility of excluding the hollow cathode keeper power supply from the PPU, and use the discharge power supply to start the cathode.

Conduct laboratory studies of the ST-25 thruster and obtain oscillograms of thruster start-up for different connection schemes.

**Solution of the problem**

The object of the study was an ST-25 Hall-effect thruster [1]. It consists of an anode unit and hollow cathode operating with barium salt insert and the heater for the cathode preheating. The general view of ST-25 Hall thruster is shown in Fig. 1. A permanent magnet is used in the central magnetic circuit of the thruster. Application of the permanent magnet along with traditional outside electromagnets gave us to minimize power consumption to create a radial magnetic field in the accelerating channel of the thruster [2].

The hollow cathode with the heater which used in the ST-25 Hall thruster structure requires for start and operating the two power supplies for the heater and keeper [3, 4].

At solving the set tasks, the connection diagram of the ST-25 Hall-effect thruster to the power processing unit (PPU) and the Xenon feed subsystem (XFS) was considered as the basic one, as shown in Fig. 2.

A typical PPU of the propulsion system includes following power supplies:

1. Controlled discharge power supply, providing stabilization of the discharge power in the accelerating channel of the thruster (130 - 150 W). The value of the discharge voltage of the discharge source at idling is 400 V, in the nominal operating mode of the thruster, the discharge voltage drops to 260 - 270 V.

**Figure 1 – General view of the ST-25 Hall thruster with the hollow cathode**

2. Controlled power supply for preheating of the hollow cathode, providing initial heating of the hollow cathode by supplying a stabilized current (4.3 - 4.5 A) to the heater. After the thruster starting, the preheating power supply is switched off

3. Voltage source of the hollow cathode keeper. The keeper voltage is 400 - 600 V, after the thruster is started, the keeper voltage is turned off.

4. A power supply for the external electromagnets of the thruster, which supplies a stabilized current to the electromagnets and allows precise adjustment of the magnetic field induction in the accelerating channel of the thruster.

The xenon subsystem for storing and feeding of the working substance, which is part of the electric propulsion system, provides the supply of the working substance flow rate to the anode unit \( (m_1 = 0.56 \text{ mg/s}) \) and the hollow cathode \( (m_2 = 0.07 \text{ mg/s}) \).

In fig. 2 introduced the following notation:

- \( Ud \) - the discharge voltage;
- \( I_{em} \) - the electromagnet current;
- \( I_h \) - the cathode heater current;
- \( U_k \) - the voltage of the cathode keeper;
- \( m_1 \) - the mass flow rate of the working gas through the anode unit of the thruster;
- \( m_2 \) - the mass flow rate of the working gas through the hollow cathode.
During the laboratory experimental testing three variants of ST-25 starting were investigated. The first variant of the process of starting an ST-25 thruster with a filament hollow cathode using a high-voltage hollow cathode keeper power supply is illustrated by the graphs shown in Fig. 3.

![Figure 2 – Typical scheme of connection the anode unit and hollow cathode of the ST-25 thruster to PPU and XFS](image)

**Figure 3 – Graphs, illustrated start-up process ST-25 Hall thruster at using the high-voltage keeper power supply**
Table 1 – Cyclogram of ST-25 Hall thruster start-up at using the high-voltage keeper power supply

<table>
<thead>
<tr>
<th>Duration, sec</th>
<th>400</th>
<th>10</th>
<th>10</th>
<th>0.25</th>
<th>2.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ih = 4.5 A</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2 PD = 130 W</td>
<td></td>
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<tr>
<td>3 Uk = 600 V, 0.5 A</td>
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<tr>
<td>4 lem = 0.85 A</td>
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</tr>
<tr>
<td>5 m1 = 0.56 mg/s</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6 m2 = 0.07 mg/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Operation modes</td>
<td>Start-up mode</td>
<td>Nominal operation mode</td>
<td></td>
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</tr>
</tbody>
</table>

The sequence diagram of the first variant of the ST-25 thruster starting process at using a high-voltage (Uk = 600 V, 0.5 A) keeper power supply is shown in Tab.1:

T0. Turn on the power supply for the hollow cathode heater (Ih = 4.5 A).
T0 + 400 s. Switching on the discharge power supply (Pd = 130 W).
T0 + 410 s. Supply of the working substance mass flow rate into the hollow cathode (m2 = 0.07 mg/s).
T0 + 410 s. Supply of the working substance mass flow rate to the anode unit (m1 = 0.56 mg/s).
T0 + 420 s. Turning off the power supply for the hollow cathode heater.
T0 + 420 s. Switching on the electromagnet power supply (Iem = 0.85 A).
T0 + 420.25 s. Turn off the hollow cathode keeper power supply.
T0 + 423 s. Switching on the electromagnet power supply (Iem = 0.85 A).

The graphs shown in Fig. 3 show that in the process of starting the thruster, the keeper voltage decreases to 25 - 30 V, and the keeper current reaches 1.3 - 1.4 A.

The second variant for ST-25 thruster starting was investigated using a low-voltage power supply for the keeper (Uk = 50 V, Ik = 0.8 A). The cyclogram of the second option for the thruster starting was similar to the one considered above, the corresponding graphs are shown in Fig. 4.
In order to reduce the mass and dimensions of the propulsion subsystem PPU, it was proposed to exclude the hollow cathode keeper power supply from the PPU structure. This voltage source is usually used only during the thruster start-up and is disconnected after the thruster start. For the power supply of the hollow cathode keeper circuits, it was proposed to use a discharge power supply, the voltage of which is supplied to the hollow cathode keeper through a 47 kΩ resistor.

The sequence of the ST-25 thruster starting for the third option of the keeper power supply is presented in Tab. 2:

1. T0. Turning on the power supply for the hollow cathode heater (Ih = 4.5 A).
2. T0 + 410 s. Supply of the working substance mass flow rate into the hollow cathode (m2 = 0.07 mg/s).
3. T0 + 420 s. Turning off the power supply to the hollow cathode heater.
4. T0 + 421 s. Short-term (1 sec) supply of an increased flow rate of the working substance to the anode unit (m1 = 7.9 mg / s), followed by the establishment of the nominal flow rate (m1 = 0.56 mg / s).
5. T0 + 425 s. Switching on the power supply of the electromagnet (Iem = 0.85 A).

The graphs of voltages and currents of the ST-25 thruster for the proposed power supply circuit of the hollow cathode keeper are shown in Fig. 5.

Table 2 – Cyclogram of ST-25 Hall thruster start-up at keeper supply from the discharge power supply through additional resistor

<table>
<thead>
<tr>
<th>Duration, sec</th>
<th>400</th>
<th>10</th>
<th>1.0</th>
<th>1.0</th>
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<tbody>
<tr>
<td>1 Ih = 4.5 A</td>
<td></td>
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<tr>
<td>2 Pd = 130 W</td>
<td></td>
<td></td>
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<tr>
<td>3 Iem = 0.85 A</td>
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<tr>
<td>4 m1 = 7.9 mg/s</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>5 m1 = 0.56 mg/s</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6 m2 = 0.07 mg/s</td>
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<tr>
<td>7 Operation modes</td>
<td>Start-up mode</td>
<td>Nominal operation mode</td>
<td></td>
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</tbody>
</table>

Figure 5 – Graphs, illustrated start-up process ST-25 Hall thruster at using for keeper supply the discharge power source
Analysis of the third option for the thruster starting, shown in Fig. 5, shows that the proposed version of the keeper's power supply necessitates a significant (more than an order of magnitude) short-term increase in the consumption of the working substance into the engine anode for a reliable engine start. A short-term increase in the flow rate through the anode significantly complicates the control algorithm of the storage and feed subsystem of the working substance, and also leads to significant surges of the thruster discharge current (Id = 1.8 A) compared to the nominal value (Id = 0.55 A) during start-up, which leads to overloads discharge power supply.

Analysis of the presented sequence diagrams for ST-25 thruster starting, as well as graphs illustrating the starting processes in Fig. 4 and Fig. 5, made it possible to propose a fourth version of the power supply circuit for the hollow cathode keeper from the discharge power supply through a resistor limiting the keeper current and an electronic switch providing a pulse supply of the discharge voltage to the keeper with an adjustable pulse duration. Such a power supply circuit for the keeper also allows a series of ignition pulses to be supplied, which increases the reliability of the thruster starting.

The process of ST-25 thruster starting at using a high-speed electronic switch is characterized by the starting sequence shown in Table 3:

T0. Turning on the power supply for the hollow cathode heater (Ih = 4.5 A).

T0 + 400 s. Switching on the discharge power supply (Pd = 130 W).

T0 + 410 s. Supply of the working substance mass flow rate into the hollow cathode (m2 = 0.07 mg/s).

T0 + 410 s. Supply of the working substance mass flow rate to the anode unit (m1 = 0.56 mg/s).

T0 + 420 s. Turning off the power supply to the hollow cathode heater.

T0 + 420 s. Pulse switching on of an electronic switch, supplying one or several pulses of discharge voltage to the keeper of the hollow cathode.

T0 + 423 s. Switching on the electromagnet power supply (Iem = 0.85 A).

The graphs of voltages and currents when starting the ST-25 thruster for the fourth version of the keeper power supply circuit at using an electronic key are shown in Fig. 6. The graphs show that when the keeper is connected to the discharge source for a short time, a keeper current arises up to 1.05 A, as a result of which an arc discharge is formed in the cathode, leading to the engine start. After disconnecting the keeper from the discharge source, the discharge current reaches the nominal value.

It should be noted that all the presented starting sequence diagrams (Table 1 - Table 3) provide for the thruster start with the electromagnets turned off. The electromagnets are turned on after starting the engine.

Table 3 – Cyclogram of ST-25 Hall thruster start-up at keeper supply from the discharge power supply through the electronic switch

<table>
<thead>
<tr>
<th>Duration, sec</th>
<th>400</th>
<th>10</th>
<th>10</th>
<th>0.25</th>
<th>2.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ih  = 4.5 A</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pd  = 130 W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Вкл. ключа</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Iem = 0.85 A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>m1 = 0.56 mg/s</td>
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<tr>
<td>6</td>
<td>m2 = 0.07 mg/s</td>
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<td>7</td>
<td>Operation modes</td>
<td>Start-up mode</td>
<td>Nominal operation mode</td>
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</tbody>
</table>
Scientific novelty

1. As a result of the analysis of the four considered startup sequences of the ST-25 Hall thruster with a filament hollow cathode, it was shown that it is possible to exclude the keeper power supply from the PPU of the propulsion system.

2. When starting the ST-25 engine, it is proposed to use the discharge voltage supplied to the keeper through a high-speed electronic switch to supply the hollow cathode keeper.

3. The sequence diagram for starting the ST-25 thruster was worked out without using a separate power supply for the hollow cathode keeper, which ensures a reliable engine starting process.

4. The accepted technical solutions made it possible to significantly reduce the weight and dimensions of the PPU of the electric propulsion system with the ST-25 thruster and place the PPU in the volume of 2U (200x100x100 mm).

Conclusions

As a result of the ST-25 Hall-effect thruster and the cyclograms of it starting investigation, the possibility of this type of Hall-effect thruster on spacecraft using was confirmed, the electric power onboard level of which is limited up to 200 W.

Bibliographic reference


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Information about authors


