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DETERMINING WORKING PARAMETERS FOR THE HALL-EFFECT THRUSTER WITH PERMANENT MAGNETS

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The object of this study is a Hall-effect thruster with a magnetic system on permanent magnets with minimal power consumption of electric energy, designed by Flight Control LLC (Ukraine). The task addressed in the study was to minimize the power consumed by the engine by excluding electromagnets from the engine's magnetic system and using only permanent magnets in the magnetic system. To solve this task, a laboratory model of a Hall-effect thruster with permanent magnets was built and the operating parameters and characteristics of the engine were experimentally determined. As a result of laboratory studies of the operating parameters of the engine with permanent magnets, the volt-ampere characteristics of the engine discharge were obtained at fixed working gas (xenon) flow rates. The dependences of engine thrust on the mass flow rate of the working gas at fixed discharge voltages were also obtained. Based on the experimental data, the dependences of specific impulse of the engine anode block on the discharge voltage, as well as the dependences of efficiency of the engine anode block on discharge voltage and the working substance flow rates were calculated. The studies have shown that in Hall-effect thrusters of low thrust, in order to minimize the specific power as part of the magnetic system, it is quite possible to use permanent magnets. In particular, for the power range (100–200) W, the values of thrust (3–10) mN, specific impulse (700–1350) s, and efficiency of the anode block (25–37) % were achieved, which corresponds to the parameters of the considered prototypes with the conventional and combined structure of the magnetic system. The results of the work could be used in practice when designing Hall-effect thrusters of low specific power

Keywords: Hall-effect thruster, permanent magnets, engine thrust, specific impulse, engine efficiency

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1. Introduction

The reduction in the mass and size of spacecraft has opened up new opportunities in the space market with enormous potential. Nano- and micro-satellites weighing from 15 to 150 kg, which are characterized by simplicity and accessibility, are capable of performing a wide range of tasks in low Earth orbit (LEO), including sun-synchronous orbit (SSO). When designing small spacecraft, the issue of constructing inexpensive and reliable propulsion systems, which most often use Hall-effect thrusters, is acute. Modern propulsion systems must meet new requirements through miniaturization and reduced energy consumption.

During the operation of Hall-effect thrusters, electrical energy is spent on the processes of ionization of the working substance, acceleration of ions formed during the ionization process, neutralization of the ion beam, operation of the hollow cathode, and generation of a radial magnetic field in the engine's accelerating channel. The radial magnetic field can be induced by both electromagnets and permanent magnets, which is especially important for low-power motors, as it saves the energy required to generate it. The use of permanent magnets eliminates the energy required to induce the radial magnetic field from the list of energy costs in Hall-effect thrusters.

Flight Control LLC (Ukraine) is designing low-power Hall-effect thrusters, in which permanent magnets are used in addition to electromagnets to induce a radial magnetic field in the accelerating channel. The next step in minimizing the specific power of Hall-effect thrusters is to completely eliminate electromagnets from the engine and use only permanent magnets. Such a technical solution has certain advantages. First, the engine design is significantly simplified by eliminating electromagnets. Second, the corresponding power source is excluded from the power supply system of the propulsion system. But such a solution can also cause certain problems, due to the fact that changing the radial magnetic field, which in this case will be constant, cannot be used to optimize the engine operating modes. That is why Flight Control LLC decided to design and conduct experimental studies of a Hall-effect thruster with a minimum specific power, in the magnetic system of which only permanent magnets are used.

The results of the design and experimental research will help determine the operating parameters for permanent magnet motors, which can be compared with the parameters of motors using electromagnets. In this regard, it is a relevant task to investigate the operating parameters of the permanent-magnet Hall-effect thruster.

2. Literature review and problem statement

A number of low-thrust Hall-effect thrusters have been designed, a thorough review of whose parameters is given in [1]. These engines provide a fairly high thrust density (>20 N/m^2), a ratio of engine thrust to power consumption (~60 mN/kW), and a specific impulse value of more than 1000 s [2, 3]. However, those works did not consider the possibility of reducing the electric power required for the operation of the Hall-effect thruster by using exclusively permanent magnets in the magnetic system.

In [4, 5], the results of designing the ST-25 low-thrust Hall-effect thruster are reported, which uses a combined magnetic system, where a permanent magnet is applied along with conventional electromagnets. The use of a combined magnetic system in the ST-25 engine made it possible to reduce the amount of electric power to induce a radial magnetic field, while maintaining the ability to regulate the induction of the radial magnetic field in the accelerating channel. The results of testing the ST-25 engine in three different vacuum chambers at different residual pressure values are given in [6]. The work made it possible to determine the parameters of the magnetic field that ensure the stability of the ST-25 low-thrust engine and its high efficiency. However, the use of a combined magnetic system did not make it possible to completely eliminate the consumption of electrical energy for the formation of a radial magnetic field in the engine channel.

Papers [7, 8] describe the design of the HT100 engine by Sitael within the MEPS program [9], aimed at constructing a low-power and inexpensive Hall-effect thruster, in which permanent magnets are used to reduce mass and dimensions. Study [10] reports the results of ground tests of this engine using alternative working gases – xenon and krypton. The tests showed the adaptability of the engine to the use of different working gases and also revealed the need for further research into the influence of the structure on the durability and efficiency of engine under conditions of long space missions. The studies presented in [8–10] showed the need for further scientific research aimed at optimizing the structure of engines using permanent magnets to increase their reliability and efficiency.

Analysis of the dependence of thrust and specific impulse on the power consumption for various low-thrust Hall-effect thrusters – IST200, IST100, BHT200, BHT100, SPT-30, CAM200 and PLAS40, operating on xenon, is given in [11, 12]. Analysis of these works reveals that the dependence of thrust on the power consumption in the range of 50–300 W is practically linear and varies from 5 mN to 20 mN. The value of the specific impulse increases with increasing power consumption from 600 s to 1600 s. The efficient operation of the engines under consideration is characterized by relatively high thrust and low specific impulse with increasing mass flow of the working substance and relatively low (about 250 V) discharge voltage. The anode efficiency of low-power Hall thrusters is typically in the range of 20 % to 45 % over a power input range of 50 W to 300 W [11]. At an input power of 150 W, a xenon-powered Hall thruster equipped with BN or BN-SiO_2 channel walls provides a thrust of about 10 mN with a specific impulse of about 1000 s and an anode efficiency of about 30–40 %, and a thrust-to-power ratio of ~65 mN/kW [12, 13].

Thus, papers [11–13] report the parameters of engines that have either only a classical or a combined magnetic system for inducing a radial magnetic field in the accelerating channel. As regards engines with a magnetic system built exclusively on permanent magnets, the features of operation and parameters of such engines were not considered in the above studies while the tasks of investigating engines with such magnetic systems were not set.

Based on our critical review of the literature [1–13], it was determined that those papers lack information on the features of operation and operating parameters – the magnitude of thrust, specific impulse, and efficiency of Hall-effect thrusters with a magnetic system built exclusively on permanent magnets. Thus, this problem has not yet been solved, and designers of low-thrust Hall-effect thrusters face this problem. All this allows us to assert that the development and experimental determination of operating parameters for a Hall-effect thruster with permanent magnets are expedient.

3. The aim and objectives of the study

The purpose of our research is to design and experimentally determine the operating parameters for a Hall-effect thruster, the magnetic system of which is built exclusively on permanent magnets. This will make it possible to reduce the electric power required for engine operation, which will contribute to increasing its energy efficiency, and will also provide designers of engines of this type with practical recommendations for their further improvement.

To achieve this goal, it was necessary to solve the following tasks:

– to experimentally determine the volt-ampere characteristics and dependences of engine thrust on the values of discharge voltage and working substance consumption through the anode block of the engine;

– to determine the calculated dependences of specific impulse and engine efficiency on the discharge voltage and mass consumption of the working substance.

4. The study materials and methods

The structure of a laboratory model of the ST-22 engine was chosen as the object of study of the Hall-effect thruster with permanent magnets [14]. A feature of the design of the object of our study is the use of permanent magnets in the magnetic system, which is designed to form a radial magnetic field in the accelerating channel. Samarium-cobalt magnets of the YXG32M type were used as permanent magnets, which have a sufficiently high Curie temperature, which allows them to be used in Hall-effect thrusters. The hypothesis of the research assumed that the use of permanent magnets would allow the elimination of electromagnet coils from the combined structure of the magnetic system of Hall-effect thrusters, and the corresponding power supply source from the engine power supply system.

The structural diagram of the anode block of the Hall-effect thruster with permanent magnets is shown in Fig. 1. The diagram shows that the magnetic system includes a central permanent magnet (8) and several external permanent magnets (10), connected by a magnetic core.

During the experimental studies, a barium hollow cathode was used, which was designed to work with a more powerful Hall-effect thruster ST-25 [4–6] (not shown in Fig. 1). For stable operation of the hollow cathode, which is designed to work with a higher discharge current, a constant voltage was applied to the cathode keeper during the experimental studies.

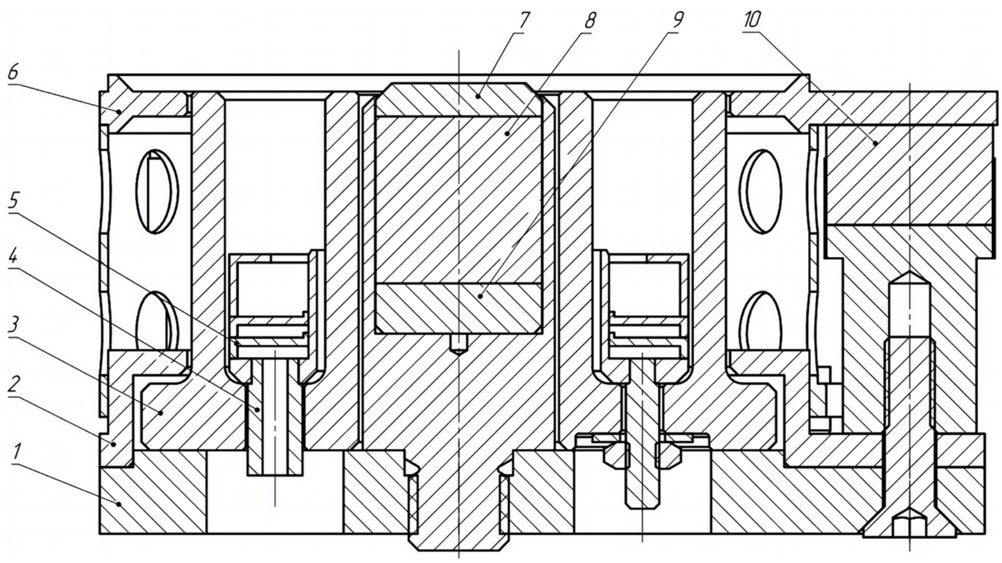

Fig. 1. Structural diagram of the anode block of the engine with permanent magnets: 1 — support flange; 2 — lower magnetic ring; 3 — accelerating channel; 4 — working gas supply tube; 5 — anode-gas distributor; 6 — front pole of the external magnetic circuit; 7 — front pole of the central magnetic circuit; 8 — central permanent magnet; 9 — lower pole of the central magnetic circuit; 10 — external permanent magnet

The general view of the anode block of the experimental model of the permanent magnet motor is shown in Fig. 2.

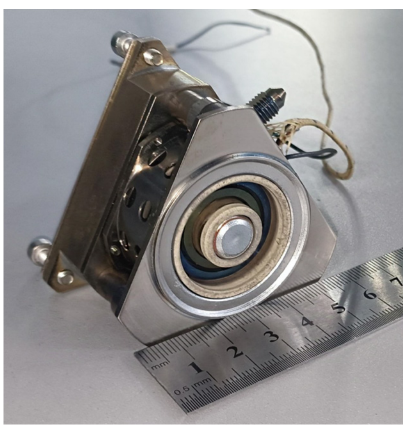

Fig. 2. General view of the anode block of a permanent magnet motor

Experimental studies of the modernized anode block of the laboratory model of the ST-22 Hall-effect thruster were carried out in a vacuum chamber, the general view of which is shown in Fig. 3. The vacuum pumps in the chamber provided a vacuum level during the studies of (3–5)×10^{-5} Torr, in accordance with the recommendations given in [6]. The main parameters of the vacuum chamber are given in Table 1. A high vacuum level during the tests was enabled by using cryogenic pumps.

Control and registration of the working substance flow rate into the anode block of the engine and the hollow cathode were provided by a laboratory supply system [6] with an accuracy of ±3 %. Adjustment was carried out by Bronkhorst valves of the FG-201CV-AAD-33-V-AA-000 series installed on both gas supply channels. This system enabled stabilization and regulation of the working gas flow rate, both through the working gas supply channel to the anode and to the hollow cathode.

During the experimental studies, laboratory regulated power supplies were used: programmable engine discharge voltage power supply – TDK Lambda GEN600-2.6; cathode keeper voltage power supply – TDK Lambda GEN100-10; cathode heater current power supply – Matrix MPS-3010L-1.

Fig. 3. General view of the vacuum chamber in which experimental studies were conducted

Table 1

Main parameters of the vacuum chamber

No.	Parameter	Value
1	Vacuum chamber dimensions, mm (diameter/length)	4,000×1,300
2	Pump capacity, L/s	33,600
3	Pressure at xenon flow rate 0.7 mg/s, Torr	(5–7)×10^{-5}
4	Chamber material	Stainless steel

The studies were carried out using the engine on/off methodology, according to the cycle diagram, with registration of electrical parameters, thrust, and substance flow rate.

To ensure the accuracy and reliability of the experimental data on the research object, experiments were planned, which were considered multifactorial. The most significant factors in the study of the engine operating parameters were the discharge voltage and the flow of working substance to the anode block of the engine. As a result of our experiments, the following operating parameters were determined: maximum thrust, specific impulse, efficiency of the anode block. These parameters fully determine the efficiency of the engine and the degree of optimization of its characteristics.

Fig. 4 shows the input signals applied to the engine during the experimental studies, as well as the output signals and calculated engine parameters obtained as a result of processing the experimental data.

A specially designed and calibrated device was used to measure the engine thrust during the experimental studies. This device makes it possible to measure the thrust value in the range from 5 to 15 mN with an error of no more than ±4 %.

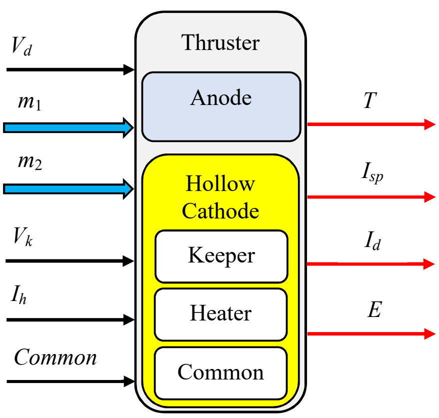

Fig. 4. Input and output variables and design parameters of the permanent magnet motor: V_d, I_d – discharge voltage and current; V_k – hollow cathode keeper voltage; I_h – cathode heater current; m_1, m_2 – working gas flow rates into the anode block and cathode; T – thrust; I_{sp} – specific impulse; E – anode block efficiency

Measurements of operating parameters were carried out for each engine operating mode by setting the discharge voltage and the corresponding working gas flow rates. The discharge voltage was set by a stabilized voltage source in the range of 175–300 V with a step of 25 V. The mass flow rate of the working gas into the anode block was set in the range of 0.4–0.8 mg/s with a step of 0.1 mg/s.

After analyzing the experimental data, the average values of the discharge current and the thrust values were determined with an error not exceeding 5 % of the average value. Other engine parameters were calculated based on these average values of the discharge current and thrust.

5. Results of investigating the operating parameters of the permanent magnet Hall-effect thruster

5. 1. Experimental determination of the current-voltage characteristics and the dependence of engine thrust on the consumption of working substance

During the experimental studies, a family of current-voltage characteristics of the gas discharge engine was determined, which is shown in Fig. 5.

Analysis of the resulting current-voltage characteristics reveals that the average value of the discharge current at a fixed value of the mass flow rate of the working substance remains almost unchanged, which indicates a high ionization coefficient of the working substance in the accelerating channel of the engine.

Dependences of engine thrust on the value of mass flow rate of the working substance at fixed values of discharge voltage, established during experimental studies, are shown in Fig. 6. The resulting experimental data show that the nature of the dependence of engine thrust on the flow rate of working substance is almost linear. This allows us to conclude that the flow rate of the working substance is the most effective way to regulate the engine thrust.

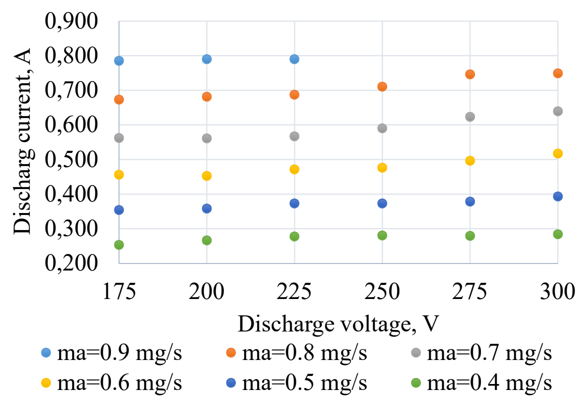

Fig. 5. Discharge current-voltage characteristics family

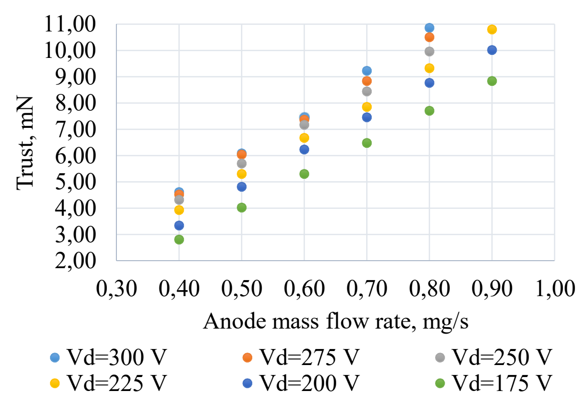

Fig. 6. Dependence of engine thrust on the working gas mass flow rate

As regards the dependence of thrust value on the discharge voltage (Fig. 7), this dependence is insignificant, therefore it is not recommended to use this parameter to regulate the thrust.

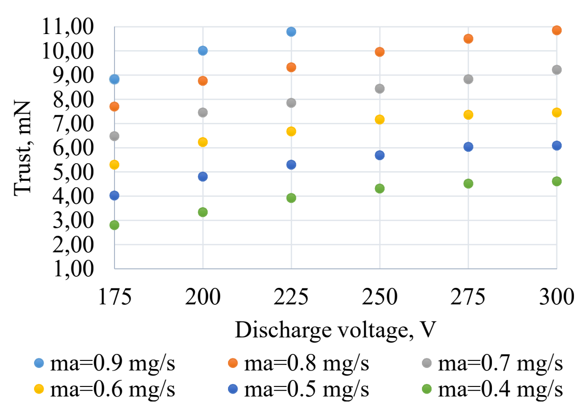

Fig. 7. Dependence of engine thrust on discharge voltage

5. 2. Determining the dependence of specific impulse and efficiency of the engine on the flow rate of working substance and discharge voltage

Based on the results of our experimental determination of the family of current-voltage characteristics and engine thrust, the dependences of the specific impulse of the anode block on the discharge voltage and the mass flow rate of the working substance were calculated. These dependences were calculated according to the known relationship [11]:

$$I_{sp} = \frac{T(V_d)}{m_1 \cdot g}, \tag{1}$$

where I_{sp} – specific impulse of the anode block of the engine;

$T(V_d)$ – engine thrust;

m_1 – mass flow rate of the working substance through the anode block;

g – acceleration of gravity.

The plots of the calculated dependences of specific impulse on discharge voltage and the working substance consumption are shown in Fig. 8, 9. It should be noted that the calculation of each value of the specific impulse and efficiency of the anode block was carried out using the engine thrust value, which was derived for the corresponding value of discharge voltage. Thus, the values of the specific impulse and efficiency were obtained depending on the discharge voltage.

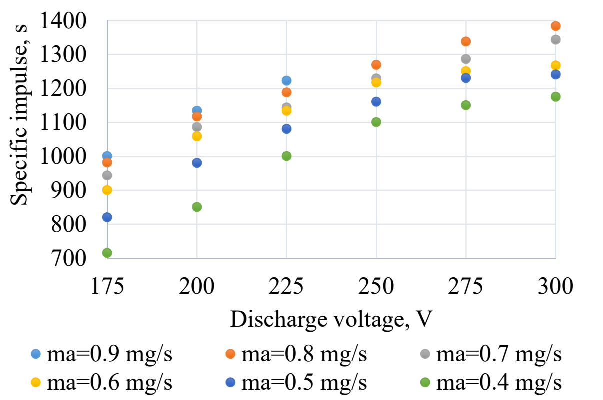

Fig. 8. Dependence of the specific impulse of the anode block of the engine on discharge voltage

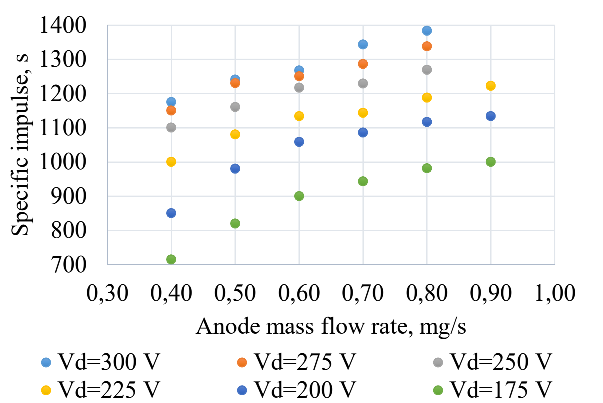

Fig. 9. Dependence of the specific impulse of the anode block of the engine on the consumption of working substance

The dependences of the anode efficiency on discharge voltage and the working substance consumption are calculated from the formula:

$$E = \frac{T^2(V_d)}{2 \cdot m_1 \cdot P_d} \cdot 100\,\%, \tag{2}$$

where E – efficiency of the anode block;

$T(V_d)$ – engine thrust;

P_d – discharge power.

The calculated dependences of engine efficiency on the discharge voltage and mass flow of the working substance are shown in Fig. 10, 11.

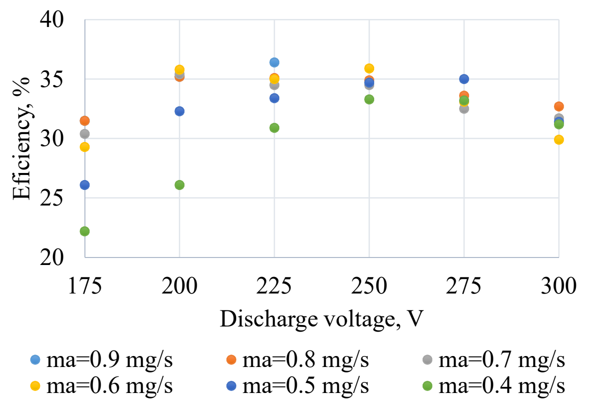

Fig. 10. Dependence of efficiency of the anode block of the engine on discharge voltage

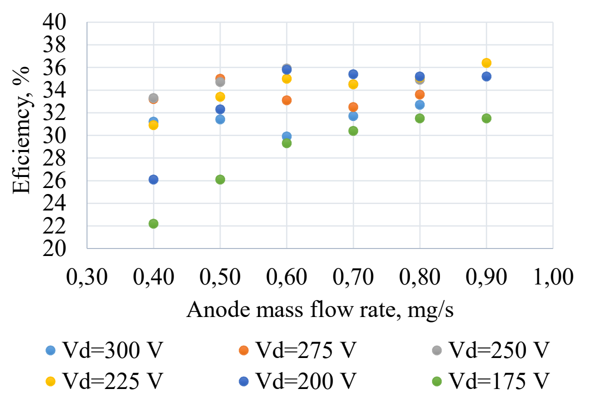

Fig. 11. Dependence of efficiency of the anode block of the engine on the consumption of working substance

Analysis of the data shown in Fig. 10, 11 allows us to conclude that when the motor operates with permanent magnets in the discharge voltage range of 175–300 V and working gas mass flow rates of 0.4–0.8 mg/s, the values of the anode efficiency are within 25–37 %.

6. Discussion of results based on the experimental determination of operating parameters for the Hall-effect thruster with permanent magnets

The results of our experimental study of the Hall-effect thruster with permanent magnets showed that the use of such a magnetic system makes it possible to significantly reduce the energy costs required for generating a magnetic field in the accelerating channel. The resulting volt-ampere characteristics of the discharge and the dependence of thrust on the mass flow rate of the working gas indicate the possibility of enabling stable operation of the engine in a given power range (100–200) W, which is critically important for its practical application in low-power spacecraft.

Our research results – the volt-ampere characteristics of discharge in the accelerating channel, the thrust, the discharge current (Fig. 5–7), the specific impulse and efficiency (Fig. 8–11) – generally coincide with the data obtained by designers and researchers of other Hall-effect thrusters [1–9] with conventional and combined magnetic systems. Namely: the thrust value is in the range of (3–10) mN; specific impulse (700–1350) s; efficiency – (25–37) %. It should be noted that the obtained value of the thrust to power ratio (40–45 mN/kW) is slightly less than that for prototypes (50–55 mN/kW). The task of obtaining the maximum engine thrust in this case was not set and may be the subject of further research.

Thus, in low-thrust Hall-effect thrusters, to minimize the specific power, it is quite possible to use a magnetic system based exclusively on permanent magnets. In addition to minimizing the specific power, the engine design is significantly simplified and the number of power sources required for the engine operation is reduced.

This study has certain limitations, which are due, firstly, to the lack of the possibility of influencing the processes of ionization and acceleration of ions by changing the induction and configuration of the magnetic field in the accelerating channel. Secondly, the limitation is that our research results are difficult to extend to high-power Hall-effect thrusters. Thirdly, in the event of discharge current fluctuations of significant amplitude, in order to reduce the amplitude of these fluctuations, it is necessary to significantly change the operating parameters of the engine, which leads to a significant change in thrust and specific impulse. A separate drawback of the study is the use of a more powerful hollow cathode from the ST-25 engine during experimental studies, which forced us to constantly maintain voltage on the cathode keeper and consume additional electrical power.

Further development of this research involve similar studies using a cathode whose parameters correspond to those of a low-power Hall-effect thruster (up to 100 W), as well as studies of Hall-effect thrusters ST-40 (discharge power – up to 600 W) and ST-100 (discharge power – up to 1500 W) with magnetic systems based on permanent magnets.

7. Conclusions

1. As a result of our experimental studies, it was shown that when using permanent magnets in the magnetic system of the motor, the obtained volt-ampere characteristics of the discharge indicate a high level of ionization of the working substance in the acceleration channel. Experimental dependences of motor thrust on the values of mass flow rate of the working substance (0.4–0.9) mg/s and the discharge voltage (175–300) V showed that it is better to use a change in the flow rate of the working substance to control motor thrust since this dependence is practically linear; the nonlinearity does not exceed 2.5 %.

2. The calculated parameters of the engine showed that the use of exclusively permanent magnets in the magnetic system of the Hall-effect thruster has made it possible to obtain engine parameters that fully correspond to the parameters considered with conventional and combined magnetic systems. In particular, the thrust value is in the range of (3–10) mN, specific impulse (700–1350) s, efficiency – (25–37) %. Our experimental and calculation data confirmed correctness of the proposed technical solutions.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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