The object of research reported in this work is the fluctuations of the discharge current in Hall thrusters. The presence of significant fluctuations in the discharge current in Hall thrusters causes a significant deterioration of the thruster parameters – thrust, specific impulse, and efficiency. The task addressed in the current work relates to determining the main factors that affect the conditions for the occurrence of discharge current fluctuations, finding ways to reduce them, and obtaining optimal values of the parameters of the Hall thruster. The review of literary sources revealed that the specified problem is typical and has not yet been solved. In order to solve this problem, studies of the ST-40M Hall thruster were carried out in order to determine the main factors that have the greatest influence on the occurrence of oscillations and means of reducing the oscillations of the discharge current. The result of the research determined that the fluctuations of the discharge current depend most significantly on the parameters of the magnetic field in the acceleration channel of the thruster. The parameters of the magnetic field are determined by the magnitude of the currents of the thruster electromagnet coils, and the nature of oscillations, amplitude, and frequency may differ significantly with a slight change in the coil currents. As a result of the study, it was found that for the values of the currents of the coils of the magnetic system of the thruster, for which the level of fluctuations of the discharge current is minimal, the average value of the discharge current of the thruster also takes a minimum value. The research made it possible to determine the optimal operating modes of the Hall thruster, which ensure, at a given level of specific power, the maximum values of thrust, specific impulse, and thruster efficiency. The conclusions from the study could be useful for most developers of electric propulsion systems based on Hall thrusters

Keywords: Hall thruster, discharge current oscillations, optimal parameters, magnetic system

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DETECTION OF THE MAGNETIC FIELD PARAMETERS INFLUENCE ON DISCHARGE CURRENT FLUCTUATIONS AND OPTIMAL OPERATION MODES OF THE HALL THRUSTER

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1. Introduction

The widespread use of electric ~~rocket~~ propulsion systems on board spacecraft necessitates the design of highly efficient low-thrust thrusters. Most often, Hall thrusters are used to solve near-Earth space problems. From the very beginning of the design of Hall thrusters, the developers faced the problem of significant fluctuations in the parameters of the thrusters, in particular, fluctuations in the values of the discharge current in the accelerating channel. Significant fluctuations of the discharge current in Hall thrusters lead to a significant decrease in the thrust of the thrusters and their efficiency. There can be several reasons for such fluctuations. First, fluctuations in the discharge current can be caused by fluctuations in the parameters of the plasma in the accelerating channel and the broken cathode of the thruster. Secondly, the fluctuations of the plasma parameters can also be caused by the inconsistency of the magnetic field parameters in the thruster acceleration channel with the conditions of the optimal modes of ionization of the working gas and acceleration of charged particles. Thirdly, the fluctuations of the plasma parameters in the thruster acceleration channel and, accordingly, the fluctuations of the discharge current can be caused by the mutual influence of the parameters of the Hall thruster and the parameters of the discharge power source. Moreover, there are reported attempts to include the thruster electromagnet coil in the thruster discharge circuit, which usually led to significant fluctuations in the discharge current and a significant decrease in the values of the thruster parameters. In this regard, the purposeful experimental studies of discharge current fluctuations are of scientific relevance.

2. Literature review and problem statement

For the first time, problems related to the occurrence of discharge current fluctuations in Hall thrusters were reported in [1]. At the same time, "abnormal wall conductivity" in the thruster channel was considered as the main cause of fluctuations of plasma parameters in the acceleration channel of a stationary plasma thruster. To ensure stable operation of the thruster, it was proposed to increase the steepness of the induction of the magnetic field in the channel, and to bring the maximum value of the induction of the magnetic field beyond the section of the thruster. However, the proposed recommendations did not look like a certain procedure that provides a solution to the problem of discharge current fluctuations. In work [2], in order to reduce the amplitude of fluctuations of the plasma parameters, it was proposed to place electric probes in the acceleration channel of the thruster, to which the voltage was applied in the opposite phase to the fluctuations of the discharge current. The effectiveness of the proposed procedure turned out to be quite low, which was associated with the problems of placing the probes in the channel and the issues related to matching the phases of fluctuations of the plasma parameters with the voltage on the probes. At certain frequencies, the amplitude of oscillations decreased, and at other frequencies, the amplitude of oscillations increased. Thus, the problem of discharge current fluctuations was not solved.

The third reason for the occurrence of significant fluctuations in the discharge current of Hall thrusters was studied by one of the authors of this article in the course of research related to the determination of the conditions of stable operation of the SPT-100 thruster at the Lewis (J. Glenn) Research Center of NASA (National Aeronautics and Space Administration) [3]. As a result of the conducted research, it was shown that when the coils of the SPT-100 electromagnet are included in the discharge circuit, it is impossible to ensure stable operation of the thruster. The operating modes of the SPT-100 and the parameters of the discharge power source filters were also determined, in which it was possible to significantly reduce the fluctuations of the thruster discharge current. However, the works did not find their continuation and did not end with recommendations and procedures aimed at significantly reducing the fluctuations of the discharge current.

As a rule, the study of fluctuations of plasma parameters in Hall thrusters is carried out in the following areas:

a) development of methods of measurement and registration of fluctuations of plasma parameters in Hall thrusters;

b) construction of mathematical models of fluctuations of plasma parameters and mathematical modeling;

c) use of external electrical circuits to reduce discharge current fluctuations;

d) study of the influence of the design of the thruster's accelerating channel on the fluctuations of the plasma parameters.

Paper [4] reports the results of the study of discharge current oscillations in Hall thrusters with a power of up to 1 kW in the oscillation frequency range of 10–100 kHz. A high-speed camera was used to record the behavior of the plasma in the accelerating channel. The authors claim that the intensity of radiation in the acceleration channel of the thruster fluctuates with the period of fluctuations of the discharge current; the concentration of excited xenon ions fluctuates with the oscillation period and is proportional to the discharge current. In addition, the amplitude of the oscillations was sensitive to the density of the applied magnetic flux, which indicates that the fluctuations of the plasma parameters are influenced by the mobility of electrons. The proposed oscillation model, which is based on experimental results, showed that the pulse transfer corresponding to the plasma fluctuations is crucial for achieving stability of the pulse transfer. But the cited work left unanswered questions regarding practical means of reducing discharge current fluctuations.

The results of the study of low-frequency oscillations of the discharge current with a frequency of about 20 kHz, which cause the deterioration of the traction efficiency and the instability of the thruster, are given in [5]. The authors show the possibility of controlling the amplitude of oscillations at a frequency of 20 kHz by changing the length of the acceleration zone. In the cited paper, the physical mechanisms of the ionization process in the acceleration channel were investigated using non-stationary one-dimensional numerical analysis, as a result of which recommendations were obtained regarding the need to reduce the length of the acceleration zone. However, the reduction of the acceleration zone can lead to a significant change in the main parameters of the thruster, but these issues are not covered in the work.

In [6], the mechanisms that cause discharge current oscillations in Hall thrusters are investigated numerically and theoretically. A one-dimensional fluid model of processes in the thruster channel is used, which is calibrated and confirmed by experimental data obtained for the SITAEL HT5K thruster. The results show that the fluctuations of the electron mobility around its distribution in the basic configuration are necessary for the occurrence of conditions for the appearance of fluctuations in the plasma parameters. In particular, the linear dependence between the fluctuations of the density of neutrals and the mobility of electrons is sufficient to cause an instability in the proposed model, which induces antiphase fluctuations of the electric field. This introduces a positive feedback on the ionization rate through two different mechanisms, one related to electron energy and the second, which is dominant in this case, related to ion dynamics. But unfortunately, practical recommendations that could be used in practice are not given in the work.

Studies [7–10] consider the development of experimental means for studying the processes of plasma oscillations in Hall thrusters. In particular, in [7, 8], the results of the development of high-speed Langmuir probes for recording plasma oscillations in the acceleration channel of the thruster are given. And in [9, 10] it is proposed to use lasers to solve similar problems. The general shortcoming of these works is the lack of practical recommendations regarding the choice of operating modes and parameter values of Hall thrusters, which would ensure the minimization of fluctuations in plasma parameters in the thruster acceleration channel.

In [11], an attempt was made to generalize the physical processes that cause discharge current fluctuations in Hall thrusters and their mathematical models. However, as a practical recommendation, it is proposed to include an RC circuit in series with the discharge power supply, which should ensure the stabilization of the discharge current of the thruster. However, the cited work does not take into account the properties of the ionization process in the thruster acceleration channel, which have the properties of a current stabilizer, and therefore the external circuits practically do not affect the fluctuations of the plasma parameters in the channel.

On the basis of a critical analysis of existing works [1–11] tackling the problem of the occurrence of significant discharge current fluctuations in Hall thrusters, it is shown that their formation leads to a significant decrease in the main values of the thruster parameters – thrust, specific impulse, and efficiency. Thus, this issue has not yet been solved, and all Hall thruster developers face this problem. All this allows us to argue that the experimental studies aimed at determining the nature and parameters of discharge current fluctuations in Hall thrusters are relevant and expedient.

3. The aim and objectives of the study

The purpose of this work is to increase the efficiency of the ST-40M thruster by optimizing the parameters of the magnetic field in the accelerating channel. This will make it possible to determine the optimal operating modes of the ST-40M thruster, which provide the greatest values of traction, specific impulse, and overall efficiency [12, 13].

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

– to experimentally determine the types of discharge current fluctuations in the ST-40M Hall thruster and the conditions of their occurrence;

– to determine the optimal operating modes of the ST-40M thruster, under which there will be no fluctuations in the discharge current, and the thruster will have the maximum values of thrust, specific impulse, and efficiency.

4. The study materials and methods

As an object of research, the fluctuations of the discharge current of the modernized ST-40M Hall thruster were considered, which differs from the previously designed ST-40 model [12] in that the structure of the insulators was changed in it, as well as a new cathode with heater was used. An emitting insert made of LaB_6 material was applied in the cathode. Making changes to the thruster design and using LaB_6 in the cathode made it possible to significantly increase thruster thrust, specific impulse, and efficiency while increasing the specific power to 550 W. The general view of the ST-40M Hall thruster with a new cathode is shown in Fig. 1.

Fig. 1. General view of the ST-40M Hall thruster

Research was conducted in a vacuum chamber (Fig. 2), which is equipped with vacuum pumps, which include:

1) two Edwards iGX 100L and Trivac D65B forvacuum pumps and one TGKine3805MBWB-B turbomolecular pump;

2) two cryogenic vacuum panels – Coolpak 6000H.

The performance of the vacuum system ensures that the initial pressure in the chamber (in the absence of supply of working gas to the anode block and hollow cathode of the thruster) does not exceed $2{\cdot}10^{-6}$ Torr. At the maximum consumption of working gas in the anode unit (2.2 mg/s) and the hollow cathode (0.17 mg/s), the pressure in the chamber does not exceed $2.5{\cdot}10^{-5}$ Torr.

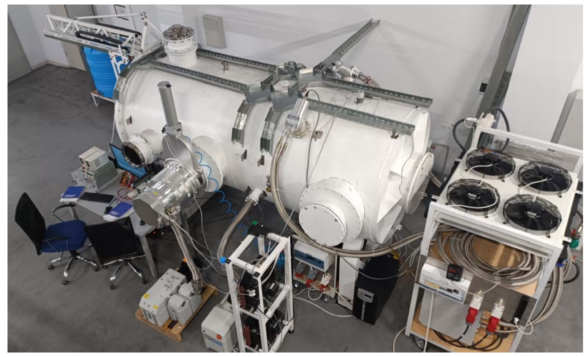

Fig. 2. Vacuum chamber in which studies were conducted

A laboratory supply system was used to supply, control, and register the mass flow rate of the working gas (Xe) to the anode unit of the thruster – m_1 and the hollow cathode – m_2 (Fig. 3). The accuracy of supplying working gas to the thruster was ±3 %. Stabilization and regulation of working gas flows in the laboratory supply system was carried out by adjustable valves FG-111B of the Bronkhorst company, both through the working gas supply channel to the anode and to the hollow cathode [13].

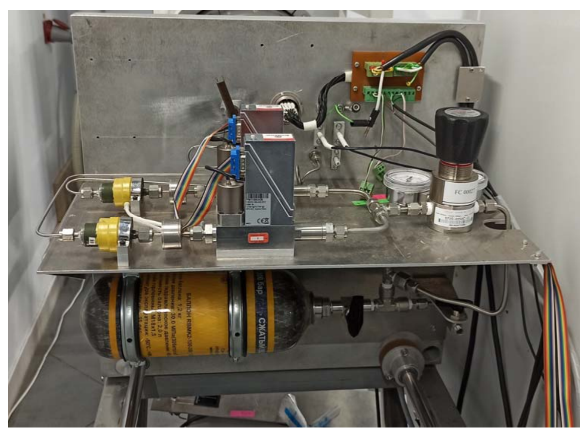

Fig. 3. Laboratory system of working gas supply

The following power sources were used during laboratory research:

1. Regulated discharge voltage source – TDK Lambda GEN600-2.6.

2. Two sources of stable current for powering the internal and external coils of the motor electromagnet – Uni-T 3315TFL-II.

3. Current source for initial heating of the cathode – Matrix MPS-3010L-1.

4. The voltage source of the cathode gatekeeper – Delta D400.

Studies of the nature and magnitude of discharge current fluctuations in the ST-40M thruster acceleration channel were conducted at different values of the discharge voltage and the mass flow rate of the working gas in the anode unit of the thruster.

The procedure for conducting the study of discharge current fluctuations in the Hall thruster, which was used in this paper, consists of two stages (the standards of the MIL-STD-461B measurement standard were taken as a basis).

At the first stage of research, control parametric tests were carried out, which correspond to the specified values of working gas consumption, voltage and discharge current, and currents of the thruster electromagnet coils.

At the second stage of research, the oscillations of the discharge current were registered and minimized by changing the currents of the internal and external coils of the thruster electromagnet. The optimization process for each given thruster operating mode was carried out 3 times. Registration of thruster parameters was carried out within 5–10 minutes. In the course of each cycle of measurements, visual control was carried out and values of consumption of the working substance, voltage and discharge current and their fluctuations, values of coil currents and thruster thrust were recorded.

To ensure the reliability of the information obtained regarding the object of research, planning of experiments was carried out, which were considered as multifactorial.

The currents of the internal I_{ic} and external coils I_{oc} of the thruster electromagnet were considered as the most significant factors during the research. As a result of experimental optimization of thruster operation modes, the following thruster parameters were obtained: maximum thrust, specific impulse, efficiency of the anode unit, and minimum thrust price. The listed parameters fully determine the efficiency of the thruster and the degree of optimization of its parameters.

Fig. 4 shows the input signals that were applied to the thruster during the research, as well as the output signals and calculated parameters of the thruster, which were obtained as a result of experimental studies.

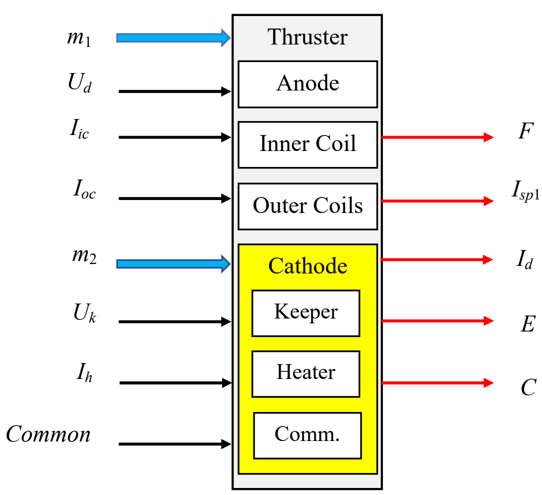

Fig. 4. Input and output variables of the ST-40M thruster and calculation parameters: U_d, I_d – discharge voltage and current; I_{ic}, I_o – currents of the internal and external coils of the thruster; U_k – hollow cathode keeper voltage; I_h – cathode heater current; m_1, m_2 – consumption of working gas in the anode unit and cathode; F –thruster thrust; I_{sp} –specific impulse of the thruster; E is the efficiency factor of the anode unit; C – thrust price

During the experimental research, the thrust measurement of the thruster was carried out by a specially designed and calibrated thrust measuring device, which provides the measurement of the thrust value in the range from 10 to 35 mN with an error that does not exceed ±4 %.

Research was carried out for each mode of operation of the thruster, 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 250–350 V with a step of 25 V. The mass flow rate of the working gas in the anode unit was set in the range of 1.5–1.9 mg/s with a step of 0.1 mg/s. For each value of the discharge voltage, such a value of the mass flow rate was set so that the value of the discharge power did not exceed 600 W, which corresponds to the maximum value of the discharge power of the ST-40M thruster.

Minimization of the magnitude of the discharge current was carried out by changing the currents that flow through the internal I_{ic} and external coils I_{oc} of the thruster electromagnet while maintaining the maximum thrust. For the identified significant factors affecting the thruster optimization process, a grid with a step of 0.1A for each factor was adopted. As a result of such a multifactorial experiment, the values of significant factors (coil currents) at which the discharge current becomes minimal were determined.

The processing of research results for each cycle of measurements was carried out using the methods of mathematical statistics. Statistical data analysis usually involves three consecutive stages:

a) critical study of data in order to identify and process emissions and other irregularities;

b) calculation of preliminary estimates of precision and average values;

c) establishment of final values of precision and average values.

After all data processing procedures of multiple direct measurement at a given error probability, the following were obtained: the average value of the measured value and its error (or the half-width of the confidence interval), which unambiguously characterize the error of multiple measurement. Based on the obtained data, the nature and parameters of the discharge current fluctuations in the ST-40M thruster and their dependence on the parameters of the magnetic field in the accelerating channel were determined.

The criterion of optimality for the selection of the parameters of the Hall thruster is to ensure high efficiency of operation, both in terms of mass and energy characteristics, provided that the required initial parameters of the thruster are achieved. The conducted studies confirmed the assumptions regarding the use of the minimum average value of the discharge current in the acceleration channel of the thruster, as well as the absence of fluctuations in the discharge current as a criterion for the optimality of the thruster.

5. Results of studying thruster discharge current fluctuations

5. 1. Determining the types of discharge current oscillations in the ST-40M Hall thruster and the conditions for their occurrence

In the course of our experimental studies of the ST-40M Hall thruster, it was established that fluctuations in the discharge current occur regularly in the entire range of the discharge voltage and the amount of mass flow of the working gas into the anode unit of the thruster. At the same time, a great sensitivity of the process of emergence was revealed. It should be noted that the process of minimizing the amplitude of the discharge current fluctuations is clearly related to the minimization of the average value of the discharge current and obtaining the maximum value of the thruster thrust, specific impulse, and efficiency. During the change of the indicated currents, not only the amplitude of the oscillations but also the nature of the oscillations changed.

Discharge current fluctuations, which were obtained as a result of research, can be categorized as follows:

1. Regular high-amplitude, low-frequency (15–20) kHz oscillations. The amplitude of discharge current fluctuations can reach 50–70 % of its average value.

2. Modulated low-frequency oscillations. The modulation frequency is much lower than the fundamental oscillation frequency.

3. Relaxation (impulse) oscillations of low frequency. The shape of the pulses can be completely different.

4. Regular oscillations of small amplitude and high frequency.

Oscillograms of typical oscillations of the discharge current of the ST-40M thruster, obtained as a result of experimental studies, are shown in Fig. 5–9.

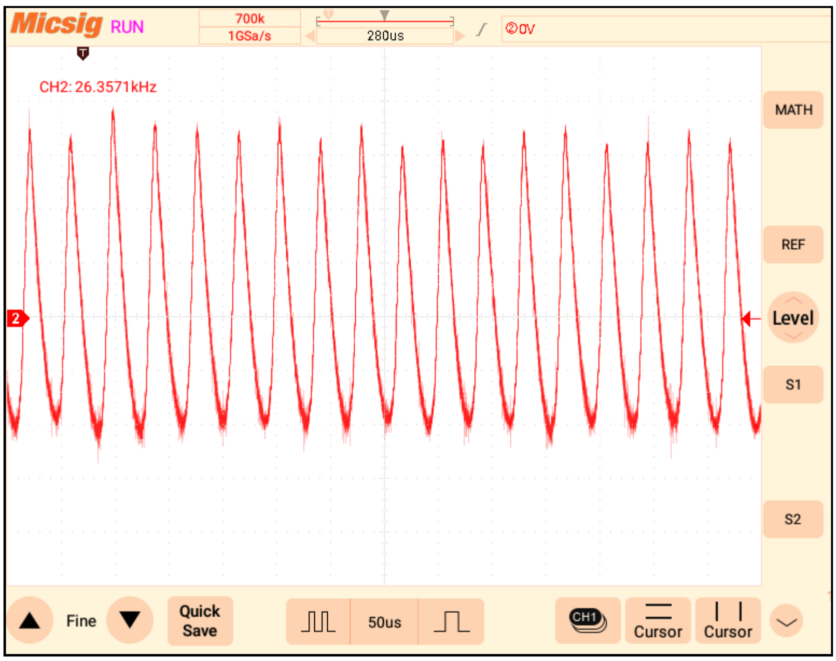

Fig. 5. Regular oscillations of low-frequency discharge current (≈26 kHz)

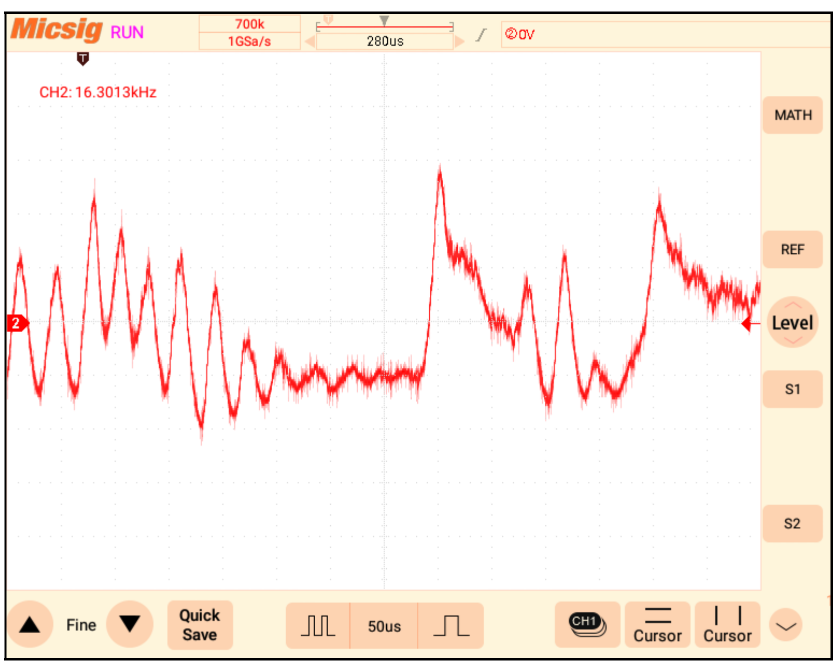

Fig. 6. Modulated low-frequency discharge current oscillations (≈16 kHz)

Fig. 7. Relaxation low-frequency oscillations of discharge current (≈16 kHz)

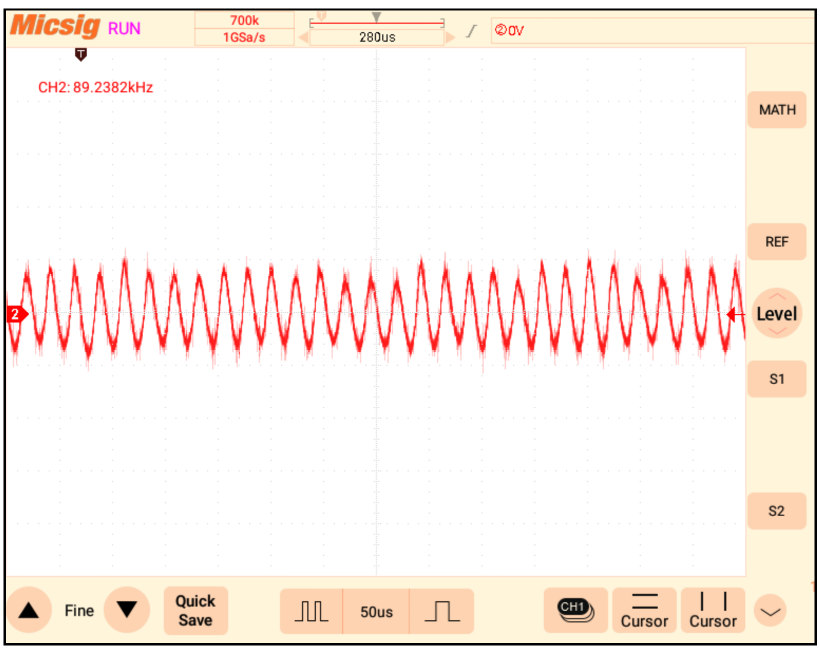

Fig. 8. Regular fluctuations of high frequency discharge current (≈89 kHz)

It should be noted that all the oscillograms of discharge current oscillations of the ST-40M thruster shown in these figures were obtained for one rated operating mode: U_d=350 B, m_1=1.7 mg/s. The difference in the oscillograms of the discharge current is due only to the different values of the currents of the thruster electromagnet coils I_{ic}, I_{oc}.

By selecting the coil currents I_{ic}=0.9 A, I_{oc}=0.9 A, it was possible to obtain a practical absence of discharge current fluctuations, as a result of which the optimal values of the thruster parameters were obtained: I_{d_min}=1.43 A, F=29 mN, I_{sp}=1725 s, E=51 %. The oscillogram of the discharge current corresponding to the optimal values of the currents of the coils I_{ic}, I_{oc} is shown in Fig. 9. Thus, on the basis of our experimental studies, it can be concluded that in the ST-40M Hall thruster, discharge current oscillations significantly different in frequency, amplitude, and character occur. The parameters of the magnetic system of the thruster, in particular, the currents of the electromagnet coils, have the most significant effect on the parameters of the discharge current fluctuation. By choosing the appropriate currents of the coils of the electromagnets, the fluctuations of the discharge current can be reduced to almost zero.

The results of experimental studies also confirmed the assumption that the minimum average value of the discharge current in the acceleration channel of the thruster, as well as the absence of fluctuations in the discharge current, can be used as an optimality criterion for choosing the Hall thruster parameters.

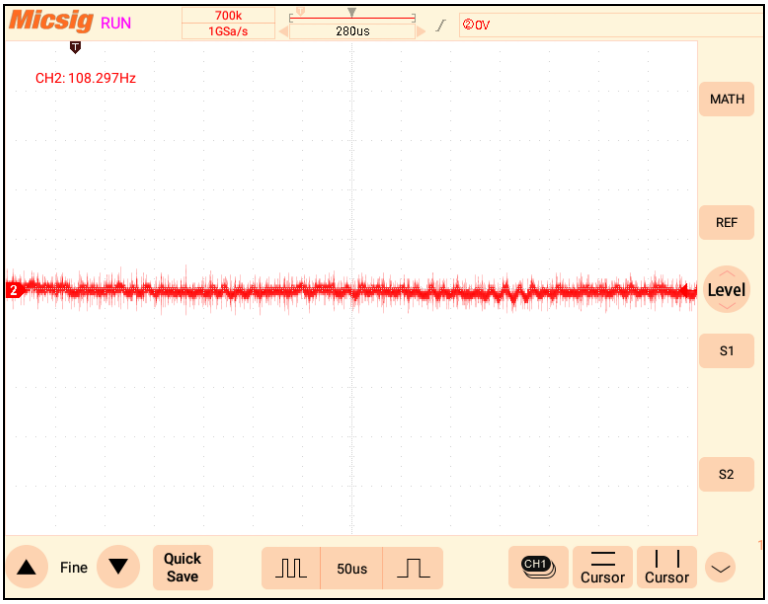

Fig. 9. Thruster discharge current oscillogram with optimal parameters

5. 2. Determining optimal operating modes of the ST-40M thruster

Our laboratory studies of the ST-40M Hall thruster showed a sufficiently high efficiency of current control of the thruster's electromagnet coils for a significant reduction and complete elimination of low-frequency oscillations of the discharge current.

However, it was established that one clear sign of the presence or absence of discharge current fluctuations is the value of the average value of the thruster discharge current at the given values of the discharge voltage and the mass flow rate of the working gas through the anode. The greater the value of the average value of the discharge current, the higher the probability of significant current fluctuations (Fig. 5), the lower the level of thruster thrust, specific impulse, and efficiency. Thus, the minimization of the average value of the discharge current is a necessary condition for obtaining the maximum values of the parameters of the Hall thruster.

The optimal parameters of the ST-40M thruster were determined during experimental studies for values of the discharge voltage in the range of 250–400 V and the mass flow rate of the working substance through the anode unit of the thruster in the range of 1.5–1.8 mg/s. The mass flow rate of the working substance through the hollow cathode was kept constant and was equal to 0.17 mg/s. Minimization of the average value of the discharge current was carried out by changing the currents I_{ic}, I_{oc} of the thruster electromagnet coils. At the same time, for a fixed value of the discharge voltage and the value of the mass flow rate of the working substance, the minimum values of the discharge current and the maximum value of the engine traction were obtained, and the values of the specific impulse, efficiency, and thrust price were obtained by calculation.

The optimal operating modes of the ST-40M thruster, which were determined during laboratory studies, and its corresponding parameters are given in Table 1.

Table 1

Optimal parameters of the ST-40M Hall thruster

U_d, V	I_{ic}, A	I_{oc}, A	F, mN	I_d, A	N_d, W	E, %	I_{sp}, s	C, W/mN
m_1=1.5 mg/s								
275	1.00	0.90	21.8	1.22	334	47.3	1452	15.4
300	0.80	0.80	22.7	1.22	367	46.9	1514	16.2
325	0.70	0.70	23.7	1.24	404	46.5	1583	17.0
350	0.80	0.80	24.8	1.24	434	47.3	1655	17.5
375	0.80	0.80	26.4	1.26	471	49.3	1759	17.8
400	1.00	1.00	27.6	1.24	496	51.1	1838	18.0
m_1=1.6 mg/s								
275	1.00	0.90	23.4	1.31	361	47.5	1465	15.4
300	0.70	0.80	24.5	1.31	394	47.7	1533	16.1
325	0.70	0.70	25.6	1.32	429	47.7	1600	16.8
350	0.80	0.80	27.1	1.34	467	49.0	1692	17.3
375	0.90	0.90	28.8	1.33	500	52.0	1803	17.3
400	1.10	1.10	30.0	1.34	536	52.5	1876	17.9
m_1=1.7 mg/s								
250	1.00	0.90	23.3	1.39	346	46.3	1373	14.8
275	1.00	0.90	25.2	1.39	381	48.8	1480	15.2
300	0.70	0.80	26.5	1.39	416	49.7	1561	15.7
325	0.80	0.80	27.5	1.40	455	48.8	1616	16.6
350	0.90	0.90	29.3	1.43	501	50.6	1725	17.1
375	0.95	0.95	31.3	1.44	539	53.5	1841	17.2
400	1.10	1.10	32.4	1.43	572	53.9	1904	17.7
m_1=1.8 mg/s								
225	0.90	0.90	22.8	1.45	326	44.1	1264	14.3
250	1.00	0.90	24.9	1.46	366	47.2	1384	14.7
275	1.00	0.90	26.9	1.46	402	50.0	1493	14.9
300	0.90	0.80	28.5	1.46	439	51.6	1586	15.4
325	0.80	0.80	29.7	1.49	485	50.4	1649	16.3
350	0.90	0.90	31.5	1.52	530	51.9	1749	16.8
375	0.95	0.95	33.6	1.50	563	55.6	1864	16.8

The optimal parameters of the Hall thruster ST-40M (Table 1) are obtained by minimizing the average discharge current and the absence of oscillations. These data make it possible to determine the main operating modes of the thruster for a given amount of discharge power N_d. Therefore, the discharge voltage U_d and current I_d, the mass flow rate of the working gas m_1 and the value of the currents of the coils I_{ic} and I_{oc}, which provide the maximum values of thrust F, specific impulse I_{sp} and efficiency, are determined.

6. Discussion of results of investigating discharge current oscillations

As a result of our research, oscillograms of oscillations of the discharge current of the Hall thruster of various nature, amplitude, and frequency were obtained (Fig. 5–8). This can be explained by the fact that the parameters of the magnetic field in the acceleration channel of the thruster significantly affect the conditions for the occurrence and existence of such oscillations. And since the parameters of the magnetic field depend to a large extent on the currents of the thruster electromagnet coils, as a result of the research, practical recommendations for choosing the values of the specified currents were obtained.

The result of our research is that a characteristic sign of the presence of minimal fluctuations of the discharge current (Fig. 9) is the minimum value of the average value of the discharge current. This makes it possible to determine the presence or absence of fluctuations in the discharge current during the operation of the propulsion system exclusively by the minimum value of the average discharge current.

The proposed approach is significantly different from most known works [1, 2, 4–7, 11] in this scientific field. In them, the main attention is paid to the formal construction of mathematical models of fluctuations of plasma parameters in Hall thrusters and mathematical modeling without specific reference to the integral parameters of the thruster – thrust, specific impulse, efficiency. Well-known mathematical models [14–16] describe, as a rule, some specific physical mechanism of occurrence of discharge current fluctuations. At the same time, when conducting experimental studies, fluctuations of the discharge current of different character were found, the mechanisms of which may be different.

A significant advantage of the approach proposed in the current paper is that in order to maintain optimal thruster operation modes (Table 1), it is sufficient to implement the use of algorithms for controlling the current values of the coils of the thruster control system. Such algorithms will ensure the maximum values of the propulsion system parameters and the absence of discharge current fluctuations. This is especially important under the conditions of long-term operation of the propulsion system on a spacecraft, during which the parameters of the thruster may undergo significant changes. The limitations of the obtained results are due to the fact that specific recommendations and optimal parameter values are obtained only for the ST-40M thruster. However, the proposed procedure for determining the optimal parameters can be used for any Hall thruster in which an electromagnet is used to generate the magnetic field in the accelerating channel.

The lack of connection between the configuration and parameters of the magnetic field in the acceleration channel of the Hall thruster and the conditions for the occurrence of discharge current fluctuations and the optimal values of the thruster parameters can be considered the shortcomings of our research. We hope to conduct these studies in the course of further research.

7. Conclusions

1. As a result of experimental studies of the ST-40M Hall thruster, it was determined that at fixed values of the discharge voltage and mass flow rate of the working substance, a slight change in the currents of the electromagnet coils causes a significant change in the amplitude and character of the discharge current fluctuations. Our research in the range of discharge voltage 250–400 V and mass flow rate of the working substance 1.5–1.8 mg/s has made it possible to determine the nature of typical fluctuations of the discharge current and their direct relationship with the values of the average discharge current.

2. The optimality criterion of the parameters of the Hall thruster was defined, which implies minimizing the average value of the discharge current in the acceleration channel of the thruster by choosing the appropriate values of the currents of the engine's electromagnet coils. The optimal modes of operation of the ST-40M thruster in the range of discharge voltage 250–400 V and mass flow rates of the working substance 1.5–1.8 mg/s were obtained, which can be used to design an electric propulsion thruster with the given parameters.

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 and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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