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AN ELECTRICALLY POWERED ION ACCELERATOR WITH CONTACT IONIZATION FOR PERSPECTIVE ELECTRICALLY POWERED THRUSTERS

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A number of characteristics of ionic and ion-plasma accelerators laboratory samples designed for electrically powered spacecraft propulsion have experimentally been studied. A large-sized vacuum chamber (2.4 m^3, 10^3 Pa) made at the Military Space Academy named after A.F. Mozhaysky provided the necessary physical and technological processes, methods and means of measurement, parameters and operation modes of the ionic accelerators with contact ionization. The samples' design features, physical processes and operating parameters were theoretically analyzed, including the use of computer simulation. The implemented and tested measuring methods, technologies and ion-physical laboratory samples' characteristics were found to correspond to the tasks of developing the promising electrically powered spacecraft propulsion.

Keywords: vacuum chamber, computer simulation, ionization, ion accelerator, electrically powered spacecraft

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ЭЛЕКТРОСТАТИЧЕСКИЙ ИОННЫЙ УСКОРИТЕЛЬ С КОНТАКТНОЙ ИОНИЗАЦИЕЙ ДЛЯ ПЕРСПЕКТИВНЫХ ЭЛЕКТРИЧЕСКИХ РАКЕТНЫХ ДВИГАТЕЛЕЙ

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Выполнены экспериментальные измерения ряда характеристик лабораторных образцов ионных и ионно-плазменных ускорителей, предназначенных для электрических ракетных двигателей космических аппаратов. Крупногабаритная вакуумная камера (2,4 м^3, 10^3 Па), созданная в Военно-космической академии им. А.Ф. Можайского, обеспечивала необходимые физико-технологические процессы, методы и средства измерений, параметры и режимы работы ионных ускорителей с контактной ионизацией. Особенности конструкции образцов, а также физические процессы с набором их рабочих параметров были проанализированы теоретически, в том числе методом компьютерного моделирования. Установлено, что реализованные и тестируемые методы измерений, технологии и ионно-физические характеристики лабораторных образцов соответствуют задачам разработки перспективных электрических ракетных двигателей.

Ключевые слова: вакуумная камера, компьютерное моделирование, ионизация, ионный поток, ионный ускоритель

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Introduction

Accelerated ion fluxes in vacuum are widely used in physical research, medicine, technologies for producing microchips and various materials, as well as in electric propulsion spacecraft [1–13]. There is a general call for systematized review of the physical problems related to electric propulsion systems (EPS) [2–6, 14–17]. It is difficult to improve the existing devices or develop new ones given the lack of comprehensive theory. A crucial task is to construct a new generation of EPS featuring alternative types of propellants, effective design and operation solutions, high reliability, extended service life, relative simplicity, and low cost.

Standard EPS are electromechanical vacuum systems where electromagnetic energy is converted to mechanical energy of propulsion. Momentum is generated using the following operating cycle: the propellant is transformed into an ionized gas/vapor phase, ions are accelerated in an electric field with subsequent neutralization of the charge of accelerated particles and free expansion of the neutralized beam into space. The main condition for generating the desired thrust is increasing the momentum of the mass accelerated in the beam, which means consuming greater amounts of propellant.

Reducing the consumption of propellant in EPS is based on obtaining high-velocity beams (50–100 km/s). The efficiency of EPS is 50% and higher, while the efficiency of chemical propulsion units does not exceed 35%. The mass of propellant on board a spacecraft amounts to 5–15% of the initial mass of the spacecraft in case of an EPS and 70% and higher in case of a chemical propulsion unit. The great advantages of the EPS are their large number of controlled firing cycles (10^6+ times) and long service lives (10,000+ hours).

Modern EPS are largely represented by electrostatic thrusters, including ion thrusters with perforated electrodes (grids) and Hall-effect plasma thrusters. The latter group includes stationary plasma thrusters, thrusters with anode layer, end Hall thrusters, and multi-stage Hall thrusters [1–17].

Grid ion thrusters are characterized by the highest efficiency (60–80% and more), high specific impulse (2,000–10,000 s; determined as the ratio between the exhaust velocity of the beam ejected into space and the acceleration of gravity (about 9.8 m/s^2)) with the voltage difference in grids up to and exceeding 10 kV. Such thrusters consume propellant efficiently and have a long service life (up to 10–12 years of operation in space).

Hall thrusters have a simpler design and require fewer power sources compared with grid ion thrusters. Hall thrusters use a magnetic field to generate electron drift motion in the direction $\overrightarrow{E}\times\overrightarrow{B}$ (transverse to the magnetic and electric vectors). Such motion of charged particles in vacuum can be attributed to the Wien filter (known since the end of the 19th century) with electron drift motion in vacuum in crossed fields rather than to the Hall effect (the classical Hall effect consists in voltage difference across a semiconductor placed in a magnetic field). The principles of the Wien filter were applied for the first time by Thompson in mass-analyzers in the early 20th century. Stationary plasma thrusters are typically referred to as Morozov's stationary plasma thrusters in Russian literature and practice, since it was Morozov who that a spatially-distributed electrostatic field could be obtained in plasma, which underlies the operation of such thrusters [2, 3].

However, the term *Hall thrusters* became widely accepted internationally. These units provide the most practically significant and reliable operating parameters, generate slightly lower impulse but a higher thrust (compared with grid ion thrusters) at the same power. The typical parameters of Hall thrusters (manufactured by Experimental Design Bureau Fakel, Kaliningrad, Russia) in different configurations range within the power/thrust ratios of 13–19 W/mN at a power consumption of 200–2500 kW. Their specific impulse amounts to 1600–2500 s. The basic parameters of Russian-made thrusters are compared in Table 1 below.

Meteor, Kosmos-1066, Kanopus-V, BKA and several other spacecraft are equipped with SPT-50 Hall thrusters operating with xenon propellant.

The following can be added for comparison: the thrust to power ratio in such devices as solar sails, laser or photon propulsion systems is 3.33–6.67 μN/kW for forward or reflected radiation, respectively.

According to the fundamental laws of physics, propulsion can be achieved in a device emitting an electromagnetic field (EMF). As the EMF is emitted, the thrust force exerts mechanical pressure on the antenna, which was predicted by Maxwell in 1873 and experimentally proved by Lebedev in 1899. It was also confirmed theoretically based on the Maxwell equations within the framework of classical electrodynamics for processes at the edge of a conductor.

The maximum pressure of an electromagnetic field on the antenna is as follows:

$$|F_{EMF}| \approx 2W/V_g,$$

where W is the power of radiation freely expanding in space; V_g is the group velocity of a wave (close to the speed of light); the coefficient 2 appears because the incident wave is reflected and emitted in the opposite direction.

To achieve noticeable accelerations with a force of approximately 1 N, significant wave power is required (approximately 150 MW).

An ion source is usually considered the most complex and critical element in the design of EPS [2, 3, 11–13, 16, 18]. The method and the characteristics of propellant ionization largely govern the required mechanical parameters. An ionizer should provide fuller ionization of the propellant so that the number of neutral particles entering the accelerating gap does not exceed 10–20% of the total number of particles exiting the ionizer. As a rule, the charges and masses of all ions should be the same, and the number of impurities should be minimal. Homogeneous processes should be maintained in the volume ionization chamber. Besides, the energy consumed by the ionizer and its mass should be minimal. The current density at the exit of the ionizer should correspond to the preset modes of the ion accelerator and the thruster as a whole.

Volume ionization by electrons is the main ionization method in stationary plasma thrusters and grid ion thrusters. The design of a volume ionizer should satisfy a certain set of requirements. In particular, in case of gas of propellant particles with the ionization cross-section σ and concentration n, the size L of the ionization chamber should exceed the ionization length λ of an electron track in gas ($\lambda = 1/\sigma n$), i.e., $L > \lambda$.

Along with these conditions, the device should have a long service life (about 10,000 h), during which fail-safe controlled switching and stable ionization should be ensured. In addition to ionization by electrons, methods of volume ionization in stationary plasma thrusters, grid ion thrusters, and prototype models of thrusters include discharge, plasma, laser, high-frequency ionization, etc. [2, 3, 14–16].

The high density of thrust in local surface areas is provided by field ionization with a strong local electric field near the cusps, e.g., with propellant in the form of liquid metal: mercury, magnesium, indium, cesium, zinc,

Table 1

Basic operating parameters of Hall thrusters

Parameter	Unit	Value		
		SPT-50	SPT-70	SPT-PPS
Thrust	mN	14.3	40	80
Specific impulse	s	860	1450	1600
Efficiency	%	26	44	48
Power	W	220	650	1350

gallium, etc., as well as electrospray capillary ionization where propellant particles are immersed in a colloidal solution. Using field ionizers with a multi-cusp surface in an ion thruster can generate a thrust of about10 mN at a power consumption of about 300 W. Colloid thrusters provide an impulse of 2500 s and a thrust of 100 μN with a thrust to power ratio of about 40 mN/kW. The volume of the ionization chamber in a colloid thruster is 0.3 dm^3, and its efficiency may reach 50%. However, due to high concentration of energy damaging microscopic areas of the surface, these thrusters cannot compete with volume electron ionizers, especially in terms of durability.

Evidently, existing EPS use a wide variety of ionization methods, including ionization and accelerated motion of charged particles obtained from compressed gases (nitrogen, argon, xenon, krypton, etc.), liquid metals, as well as colloidal solutions of organic substances. It is believed that such volatile solids as iodine, teflon, etc., may have good prospects. Despite a large number of studies, many propellant materials have only been tested in laboratory setups. The EPS used in spacecraft mainly operate with xenon because it has several advantages: chemical inertness, sufficiently high atomic mass and ionization cross-section, acceptable ionization energy. However, due to its high cost and limited resources, it is expedient to replace xenon with an alternative propellant. Consequently, a novel design of an EPS has to be developed for such propellant.

In this regard, surface, or contact ionization distributed over the surface of a solid seems quite interesting [17–23]. Contact sources equipped with a surface ionizer where cesium vapor passed through a porous tungsten membrane were tested in electrostatic ion thrusters [2–6]. However, for reasons that are now clear, the experiments met only with limited success and were not continued.

Currently, with further advances made in the theory and technology of porous materials, a new stage in surface ionization studies appears to be more justified. The probability of electron tunneling and surface ionization in a porous material can be increased due to new materials and technologies, unsteady processes, increased energy of neutral particles and electrons in the material, and surface heterogeneity [12, 13, 16–23].

Extensive experimental studies should be conducted in ground laboratories to develop novel designs. Surface ionization combined with implementing and monitoring a range of ion-plasma processes should play a major role.

Ground tests of spacecraft prototypes equipped with EPS are carried out in vacuum chambers with a large volume characterized by a high pumping speed. They include a VU-M chamber with a vacuum volume of 2.4 m^3 and a pressure of $1 \cdot 10^{-3}$ Pa, designed at the Military Space Academy named after A.F. Mozhaysky [24, 25].

The chamber was used in a series of studies conducted by the team comprising staff members from the Military Space Academy named after A.F. Mozhaysky and Peter the Great St. Petersburg Polytechnic University. Parameters were measured, and theoretical analysis (including computer simulation) was carried out for physical processes, as well as for operating parameters of laboratory prototypes of ionic and ion-plasma accelerators for electric propulsion systems used in spacecraft. The vacuum chamber provides the necessary processes, measurement methods and tools, operating parameters and modes of ion accelerators.

This paper describes the prototypes, the main methods for testing them, the stages and characteristics of the analysis, and results of experimental and theoretical studies.

Experimental methods and equipment

Characteristics of experimental prototypes. The required parameters of the prototypes to be tested were obtained by computer simulation (primarily using the Computer Simulation Technology (CST) package) [26–30]. This approach allowed to obtain the size and shape of the electrodes as well as the current-voltage characteristics of the charged particle flux in the injector circuit and distributions of particle velocity and electric field with respect to the coordinates in the accelerator volume. Additionally, new physical and technological solutions were introduced, and an ion-mechanical algorithm was used to determine the thrust in different sections of the accelerator with varying operating modes [31–35]. The following parameters of the experimental prototypes were measured:

electric voltage of ion acceleration,

ion drift current in the accelerator,

ionization coefficient of the vapor-gas flow injected,

neutralization coefficient of the accelerated ion flux,

beam pressure force.

Based on the obtained values, we determined the main performance characteristics of the ion thruster developed.

Fig. 1 shows a typical block diagram for the experimental prototype in the form of a single-stage linear DC accelerator and an electrical circuit of the measurements. The ionized gas flow of the propellant is injected into accelerating gap *4* via ionizer *1*, where drift current *5* of accelerated ions is generated. Due to the Coulomb force, ions are attracted to the charges induced on grids I and II. This generates ion acceleration and thrust. The accelerated ions are neutralized in neutralizer *7*; these particles no longer generate thrust after that and expand into vacuum as beam *8*. The power of source *10* is transferred to the ion flux in gap *4* and is then carried away in the form of a kinetic energy flux by a beam of neutral particles.

Fig. 2 shows a simplified schematic representation of the experimental prototype with ion trajectories in the accelerating gap, obtained using CST.

Fig. 3 shows a photograph of a simple two-electrode experimental prototype (corresponding to the scheme in Fig. 2) tested.

The tested device is based on surface or contact ionization in the module injecting the ion flux into the acceleration section. Ionization with positively or negatively charged

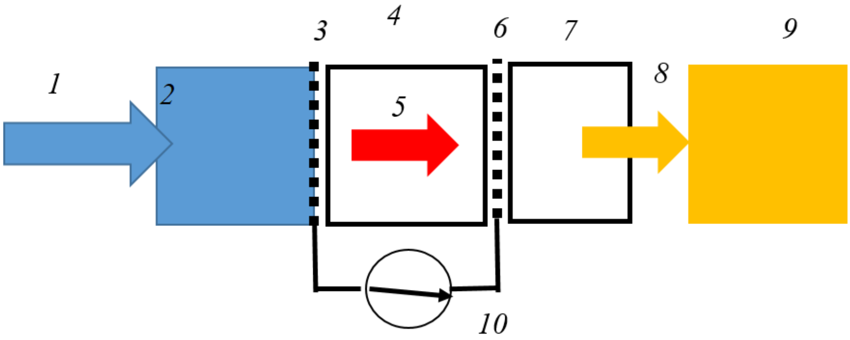

Fig. 1. Block diagram for experimental prototype and electric circuit for measurements (cation generation):
gas flow of propellant *1*; ionizer *2*; electrodes *3, 6* generating the electric field; accelerating gap *4* and ion drift current *5* in the gap; neutralizer *7*; beam *8* of neutral particles; beam impulse meter *9*; EMF source *10*

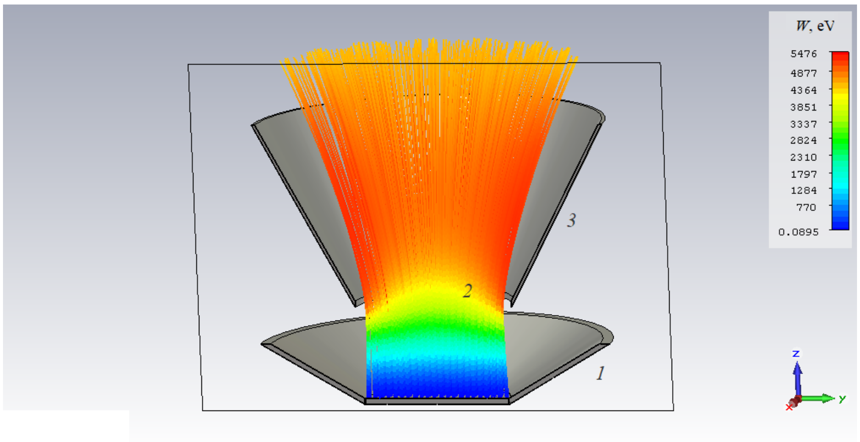

Fig. 2. Schematic representation of two-electrode prototype with ion trajectories in accelerating gap, obtained using the CST package
(the black line marks the boundary of the computational domain):
electrode *1* with ionizer distributing gas, ion-plasma flow *2*, electrode *3* generating an electric field; the color scale reflects the energy spectrum of the plasma

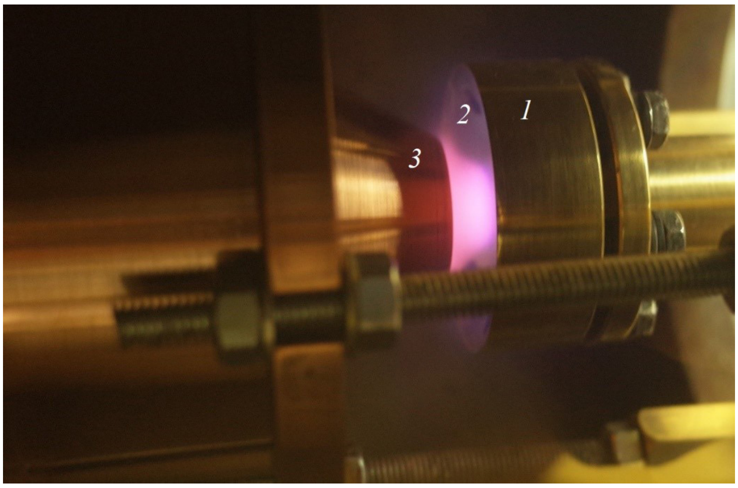

Fig. 3. Photograph of experimental prototype tested (see Fig. 2):
electrode *1* with ionizer, ion-plasma flow *2*, electrode *3* generating the electric field

particles generated occurs due to electron tunneling from a neutral particle to the surface or in the opposite direction. The experimental prototype used a structured microporous ionizer distributing gas with a flat electrically conductive surface (*1* in Fig. 3), manufactured in accordance with the description given in [23]. Aside from efficient generation of ion flux and plasma, such a spatially developed surface made it possible to focus the ion flux in the electrostatic field of the accelerator. Electrodes *1* and *3* (Fig. 3) were made of copper. The diameter of the gas-distributing ionizer was 25 mm, the gap between the electrodes was varied in the range of 2–20 mm.

The measured parameters of the experimental prototype were compared with the results of computer simulation as well as with the known values typical for the best modern devices.

Experimental vacuum chamber. The experimental prototypes of electrostatic ion accelerators were tested in a large VU-M vacuum chamber, maintaining the necessary parameters of processes and operating modes, equipment and technologies were provided [22, 23].

The parameters of ion and ion-plasma processes, including the following quantities, were measured in the tests:

voltage at the gaps between the electrodes in the acceleration module;

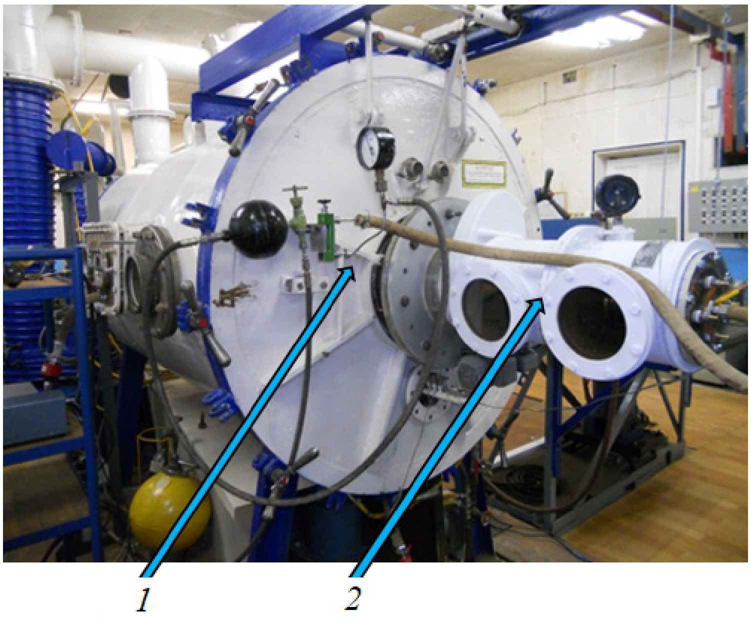

Fig. 4. Photograph of main VU-M vacuum chamber (*1*) with instrument module (*2*)

electric currents in the circuits of the accelerator electrode;

mass flow rate of propellant in the gas distributor channel;

characteristics of the radiation in the visible range;

mechanical thrust generated by the beam of particles.

The measurements were performed with continuous and pulsed high-voltage power supply. The measured parameters of the experimental prototype were compared with both theoretical and standard parameters of existing and newly proposed ion thrusters.

The experimental prototype was placed in the instrument module connected to the main VU-M vacuum chamber with a volume of 2.4 m^3 through a gate valve (a photograph of the chamber with the instrument module is shown in Fig. 4).

The instrument module was a cylindrical metal structure with a vacuum volume of approximately 0.03 m^3. The gate valve was installed between the flange and the cylindrical body. Such a technical solution made it possible to quickly change experimental prototypes in case of depressurization and subsequent rapid bypass pumping of the instrument module. Vacuum pressure was maintained in the main vacuum chamber. The instrument module had two transparent windows to record visible radiation, as well as an end flange for mounting the tested prototype, high-voltage leads, and a choke to supply propellant gases. The mechanical impulse of the beam was measured using a ballistic pendulum installed in the instrument module.

Fig. 5 shows a scheme of the VU-M vacuum chamber. The required vacuum pressure was maintained during the tests in the main chamber as well as in the instrument module upon propellant gas supply.

The vacuum pumping system and control equipment of the VU-M vacuum chamber included the following components:

two NVBM-5 oil-vapor booster pumps;

NVDM-400 oil-vapor diffusion pump;

TMN-500 turbomolecular pump;

piping system with shutoff valves and gates;

vacuum gauge heads;

backing-vacuum system, including mechanical pumps, a piping system with shutoff valves and gates, and vacuum gauge heads;

measuring equipment.

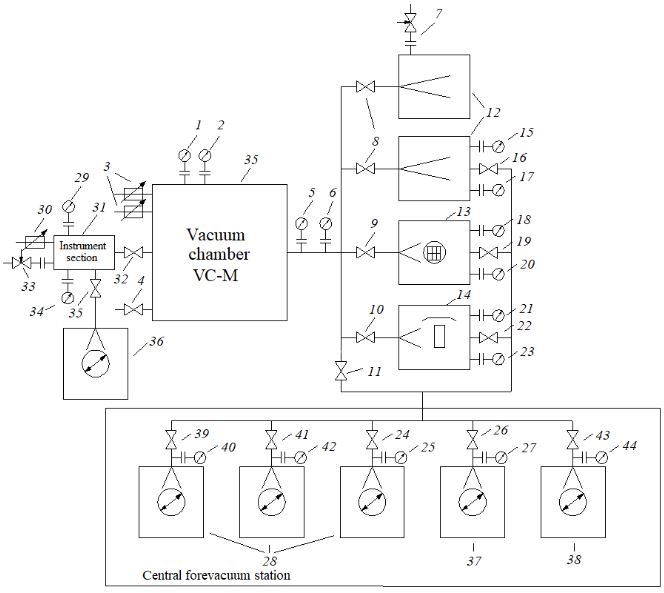

Fig. 5. Scheme of VU-M vacuum chamber:
PMT-2 thermocouple gauge heads *1*, *5*, *15*, *18*, *21*, *25*, *27*, *29*, *40*, *42*, *44*;
PMI-2 ionization gauge heads *2*, *6*, *17*, *20*, *23*, *34*; lead-in wires *3*, *30*; leak valves *7*, *33*;
valves *4*, *8–11*, *16*, *19*, *22*, *24*, *26*, *32*, *35*, *39*, *41*, *43*; NVBM-5 high-vacuum oil-vapor booster pumps *12*;
TMN-500 high-vacuum turbomolecular pump *13*; NVDM-400 high-vacuum oil-vapor diffusion pump *14*;
VN-6G backing-vacuum pumps *28* with oil seal; instrument module *31*; VK-M vacuum chamber *35*;
VN-461M backing-vacuum pump *36* with oil seal; VN-6Gm backing-vacuum pump *37* with oil seal;
VN-7 backing-vacuum pump with oil seal *38*

The operation of the VU-M vacuum chamber is characterized by the following parameter values:

residual gas pressure (without propellant gas supply) no higher than 10^{-3} Pa;

pressure upon propellant gas supply no higher than 10^{-2} Pa;

pumping time (from atmospheric pressure to residual gas pressure below $1\cdot10^{-3}$ Pa) no more than 4 h.

The total capacity of the high-vacuum pumps comprising the VU-M chamber was approximately 18 m^3/s at a pressure of 10^{-1} Pa, meeting the condition for free passage of ions in the accelerating gaps between the electrodes at an operating pressure upon gas supply.

The mass flow rate of the gas supplied was measured and controlled using an RS-3A rotameter. The mass flow rates for different propellant gases used during the experiments (compressed air, helium, argon, etc.) were varied in the range of 0.5–15 mg/s. The upper limit for air was 0.06 m^3/h, the measurement error did not exceed ±4.0% of that value.

The rotameter was calibrated by atmospheric air. The mass flow rates of propellant gases were found by recalculation by the following formula:

$$Q_{wm} = Q_{a.gr}\sqrt{\frac{\rho_{a.gr}}{\rho_{wm}}}, \qquad (1)$$

where $Q_{a.gr}$, m^3/h, is the air flow rate during calibration; $\rho_{a.gr}$, kg/m^3, is the air density during calibration; ρ_{wm}, kg/m^3, is the density of the propellant gas fed into the vacuum chamber.

The mass flow rate of propellant ρ at the inlet to the gas distributor was determined based on the following relation:

$$\dot{m} = \dot{m}_{wm} = Q_{wm}\rho_{wm} = Q_{a.gr}\sqrt{\rho_{a.gr}\rho_{wm}}. \qquad (2)$$

Mass flow rate of the propellant and ion current in the injector circuit in the accelerating gap were measured simultaneously during the experiments, which made it possible to determine the ionization coefficient for propellant atoms in the gas flow using the following equation:

$$K_i(\dot{m}, I) = [(e\dot{m}/\mu I) - 1]^{-1}, \qquad (3)$$

where $\dot{m}$, mg/s, is the mass flow rate; I, A, is the ion current; μ, mg, is the ion mass; e, C, is the electron charge.

The ionization coefficient depends on the geometric and physical parameters of the experimental prototypes.

The approximate estimate of mechanical thrust is based on formally accounting for the mechanical impulse of the beam:

$$F_T\left(z = d\right) = \frac{dm}{dt}\bullet v = \sqrt{\frac{2\mu U_d}{q}}\bullet I,$$

where U_d, V, is the voltage; q, C, is the ion charge; v, m/s, is the ion velocity at the exit from the gap, d, mm, is the gap width.

Since the expression does not account for elastic interactions of ions with neutrals, resonant charge exchange, radiation losses, and ion scattering in the acceleration module, it was used only for initial rough estimation.

The supply power of the stationary accelerator is converted to the power of ion drift motion in the gap, heat and radiation losses. The mechanical properties of the stationary ion thruster on the test bench correspond to the idle mode (in terms of power consumption) when the kinetic energy of the device amounts to zero.

Results and discussion

When DC voltage in the range of 0–5 kV was supplied to the ion accelerator at zero propellant flow, no discharge phenomena (breakdowns) were observed, and the measured currents in the acceleration module circuits were close to zero.

With voltage switching and propellant gas supply, the ion accelerator was brought into operation almost with zero lag. The measured current in the injector circuit reached its maximum of approximately 1 A, and the value depended on the gas type, the voltage (up to 5 kV), and the velocity of the gas flow supplied. The switching threshold (the average value of electric intensity in the accelerating gap) was approximately 250–500 V/cm for different propellant gases. The focused flow was observed to glow brightly, which is typically due to charge and energy relaxation of the ion flux. The glow was uniformly distributed over the surface of the microporous injector and remained stable during continuous testing. In particular, visible radiation from the accelerating gap of the experimental prototype (Fig. 3) was obtained with dry atmospheric air supplied, accompanied by generation of negative ions. Similar results were obtained for different propellants and positive ions.

Figs. 6 and 7 present typical experimental characteristics and their extrapolating curves

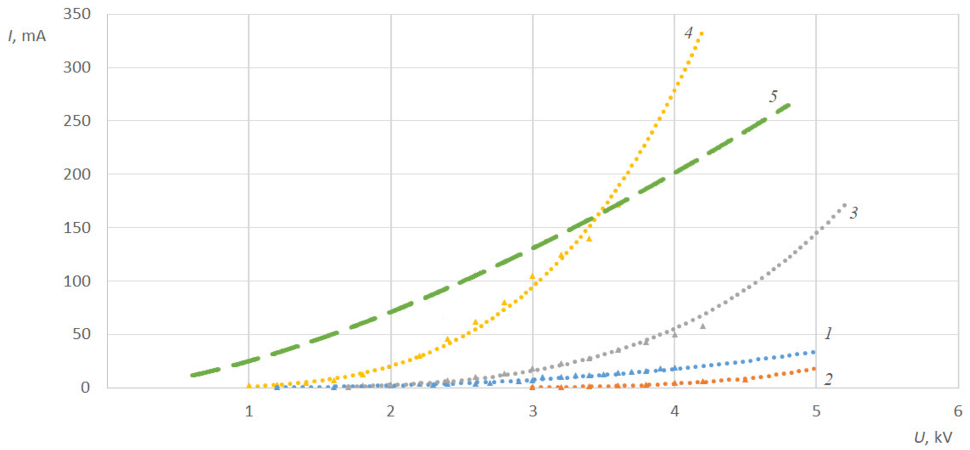

Fig. 6. Typical experimental current-voltage characteristics (points) of negative ion flux in injector circuit and their extrapolating curves (lines) for different propellants and mass flow rates $\dot{m}$:
air (*1*), $\dot{m}$ = 8 mg/s; SF_6 gas, $\dot{m}$ = 3, 6 and 9 mg/s, respectively (*2*–*4*).
The curves are given for d = 16 mm, h = 4 mm (*1*–*4*); *5* is the theoretical curve obtained using the CST package for the conditions corresponding to dependence *4*.
Extrapolating power-law relationships are summarized in Table 2.

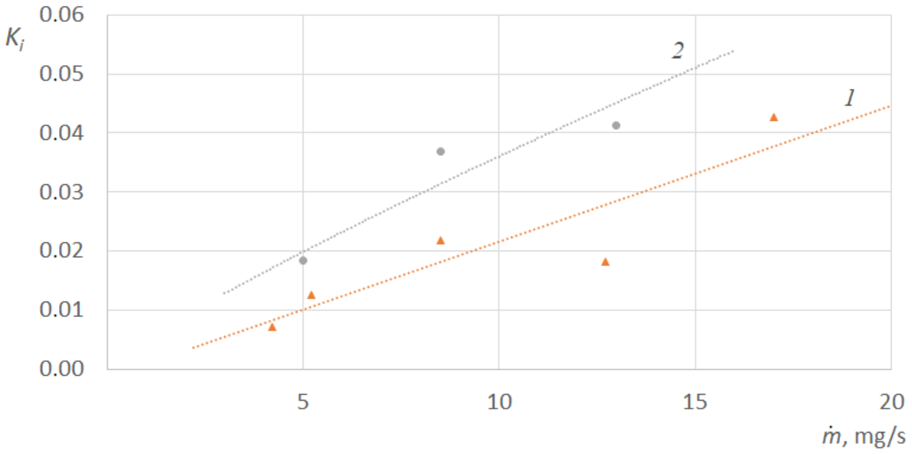

Fig. 7. Typical relationships between ionization coefficient and mass flow rate of propellant (see Eq. (3)) for two values of supplied voltage U, kV: 2.5 (*1*) and 3.0 (*2*);
The propellant is the SF_6 gas, d = 12 mm, h = 3 mm

for ion current in the injector circuit depending on the DC voltage supplied at different mass flow rates of the propellant, and for ionization coefficient depending on the mass flow rate of the propellant mass. Data were obtained for two distances between the electrodes d and two thicknesses h of the microporous plate. To provide a comparison with experimental data, Fig. 6 shows curve *5*, which is a theoretical dependence obtained with CST for the conditions corresponding to the experimental dependence *4*. Extrapolating power-law dependences are summarized in Table 2.

According to the form of the extrapolating power-law dependences, the theoretical current-voltage characteristic *5* given in Fig. 6 for the computer model (see Fig. 2) corresponds to the kinetic ion model described by the Child–Langmuir law (three-halves-power law). However, the experimental curves obtained in a wide range of modes exhibited considerable differences and peculiarities in terms of the current increase. This indicates the influence of ion-plasma phenomena, including strong radiation effects, collisions, neutralization, and resonant charge exchange.

Table 2

Extrapolating functions for current-voltage characteristics in Fig. 6

Curve	$I(U)$ dependence
1	$I_1 = 0.3244U^{2.8949}$
2	$I_2 = 0.0004U^{6.7266}$
3	$I_3 = 0.1466U^{4.2848}$
4	$I_4 = 25.178U^{1.5000}$

Note. The given functions correspond to the data in Fig. 6 only.

Furthermore, the processes were of a general quasi-stationary nature and were not accompanied by any uncontrolled discharge phenomena. Typical relationships between the ionization coefficient and the propellant mass flow rate (Fig. 7), calculated on the basis of the experimental curves according to Eq. (3), correspond to an approximately linear increase of plasma generation effects in a wide range of parameters.

Conclusion

It has been established in the experiments that proper methods and means of measurement, values of process parameters, and operating conditions at a mass flow rate of different propellant gases (air, helium, argon, etc., in cation and anion generation modes) within the range of 0.5–15 mg/s were ensured in the vacuum chamber.

Measurements and analysis of the characteristics of the experimental models of ion accelerators have also revealed that the calculated and experimental ion-physical characteristics of the tested prototypes correspond to the current tasks. The given prototypes have the following properties:

enhanced surface ionization;

ion and plasma ion bipolar modes;

uniform distribution of radiation and temperature over the developed surface of the injector;

ion injection with almost zero lag.

It has also been established that it is possible to use different propellant alternatives other than xenon.

We have found that the ion-physical characteristics of the laboratory prototypes with contact ionization implemented and tested can meet the requirements for developing promising electric propulsion units.

We assume that the developed unit with a novel physical and technological design and the given characteristics will be of interest for developing new promising equipment. In general, the experimental setup, its measuring and technological capabilities, as well as the designs of prototypes lay the foundations for further in-depth research and development of electric propulsion units.

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