Investigation of the characteristics of an ion engine with a microwave generator plasma

I S Vavilov, P S Yachmenev, V V Fedyanin, P V Stepen', A I Lukyanchik and K I Zharikov
Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

E-mail: vava-igg@mail.ru

Abstract. This paper presents the results of an experimental study of the velocity of ionized nitrogen flowing from the working chamber of an experimental sample of the primary accelerating system of the ion engine into the vacuum space. The main method of research was chosen calorimetric method. The design of a small spacecraft jet propulsion system with ionized gas acceleration in the high-frequency gap of a microwave generator is proposed. The object of the study is a prototype of the primary ion engine accelerator system with a solid-state microwave plasma generator and an accelerating gap. The study showed that a 3-watt microwave generator together with a pulsed voltage source of an accelerating potential difference of 1 W at a nitrogen consumption of 2.5 mg/s creates an ion jet whose speed reaches 30 km/s. The current of the ion jet was 2-2.5 mA. The field strength of the accelerating potential difference was 4450 V / m.

1. Introduction
The relevance of developments in the field of space propulsion to enable controlled motion of small satellites of nano-class (weighing 1 to 10 kg) due to objective reasons: miniaturization design of small spacecraft, due to widespread knowledge in the field of space microelectronic components; economic feasibility in terms of finding ways to reduce the cost of space equipment and technology while preserving the completeness of tasks; the need to develop the domestic scientific and technical base in the field of engine building for micro- and nanoclass devices in the conditions of fierce global competition for new sources of natural resources, taking into account the geopolitical features of our time. As part of solving the problems of miniature engine building, the area of increased efficiency of jet propulsion is shifting towards ion-plasma technologies. This niche has not yet been filled, but there is an increased interest of the world engineering and scientific community, both in powerful plasma engines and micro-thruster of small spacecraft. The problem of the further development of satellites nano-class lies in the provision of their controlled motion. Unmanaged vehicles have a short period of active existence, and the low energy of the device does not allow you to install complex equipment for scientific, military or economic purposes on Board. The low reliability of the small spacecraft (SSC) nanoclass is compensated by the low cost of components and preparatory work and the ability to launch multiple satellites simultaneously. Without the propulsion system it is impossible to implement the main advantage of the apparatus of nano-class – group the ability of solving problems by combining them.

In the field of engine building for ultra-small spacecraft, there are no uniform rules and generally recognized schemes. This area is new, because small nano-class spacecraft have recently appeared and have taken a separate place in space technology. Customers’ requirements remain unchanged: high...
efficiency with low power consumption, reliability and small weight and size characteristics. Therefore, any technical solution in the field of miniature engine building that differs from previous solutions and increases efficiency is an innovation.

The early works of authors (e.g. [1]) and a series of deliverables on the project "Development and design of electrothermal microjet thruster ammonia with microwave heating element for correcting propulsion of small spacecraft" (funding RFBR) was devoted to the development of the concept of a jet motor with power up to 10 W with accelerating microwave and RF clearance. A distinctive feature of this device, unlike most designs of ion-plasma engines, is the absence of accelerating and focusing magnetic fields, which greatly simplifies, reduces the cost, facilitates the design and reduces the power consumption. The second feature is the transition from RF plasma generators to microwave generators, which significantly reduces the power required for gas ionization and the overall dimensions of the device.

In the course of practical implementation, the initial concept has undergone significant changes. Initially, the microjet thruster design was a source of ions with plasma generation in a microwave discharge followed by ionized gas acceleration with a constant potential difference and further acceleration of ions in the clearance of a toroidal volume resonator at present. Now the main accelerating system is a linear accelerator between the grids of the ion optics. Thus, it is possible to implement a two-clearance acceleration scheme for ionized gas, instead of the one-clearance scheme presented in the concept.

Work on creating a microjet thruster with plasma acceleration in the microwave gap (AMT) is being carried out at the material and technical base of the scientific research laboratory Omsk state technical University "The propulsion system of micro-thrust small spacecraft" ("PSMT SSC").

2. Formulation of the problem

The main task of the authors’ work is to study the high-frequency low-temperature ionization of gaseous working bodies in reactors based on solid-state RF and microwave elements and to study the gas-dynamic, electrical and thermal parameters of a plasma jet flowing into a space with a low background pressure from the working part of a prototype ion-plasma microjet thruster and accelerated in a high-frequency gap.

This article presents the intermediate results of the study of ionized gas flow in terms of determining its velocity by the calorimetric method.

Problems solved in the course of research and reflected in this work:
1. Develop and manufacture a prototype of the first ion-plasma microjet thruster acceleration system;
2. Hold experimental studies to determine the current of the ionized gas and its energy and subsequent theoretical processing of the results of the experiment in order to verify the method.

3. Theory

Calorimetric power measurement methods are the most versatile and have high measurement accuracy. It is customary to distinguish two main groups of calorimetry methods: compensation methods and direct temperature measurement during the process [2].

The paper presents the results of calorimetric studies based on periodic measurement of the temperature of the heat receiver, with a step-by-step energy supply to the working gas in the working chamber of the prototype of the first ion microjet thruster accelerator system.

The prototype of the first accelerating system of the accelerator microjet thruster (AMT) is made using additive technologies according to a modular scheme. This scheme allows you to combine and add sections, which greatly facilitates experimental testing, setting and taking readings. In fig. 1 the current experimental prototype of the first accelerating AMT system is presented. Positions in fig. 1 are indicated by: 1 -neutralizer grid; 2 -fitting a measurement of the total pressure in the chamber AMT; 3 -fitting of measuring the static pressure in the chamber AMT; 4 -pipeline for supplying gas to a working chamber AMT; 5-gas cooling system for the microwave generator transistor. The mass flow rate of nitrogen can be estimated by a Pitot tube embedded in the gas section of the experimental prototype of the AMT. The total and static pressures in the prototype's working chamber, as well as
the static pressure in the supply line, were determined by the pressure gauges (fig. 1 b). Device № 1 (fig. 1 b) measures the excess static pressure in the supply line \( (P_1) \), the device number 2 – the total pressure in the working chamber of the prototype \( (P_2) \), the device number 3 – the static excess pressure in the working chamber of the prototype \( (P_3) \). The electron current in the neutralizer grid was measured by the pointer-type microammeter (pos. 4, fig. 1 b).

![Prototype of the first AMT accelerator system](image)

**Figure 1.** Prototype of the first AMT accelerator system: a-assembled; b - in operation when when measuring the electric current of the jet and nitrogen pressure in the AMT prototype chamber

For fig. 2 the gas section of the AMT prototype is shown separately. Position 1 indicates the fitting for determining the static pressure in the supply line, pos. 2-fitting for measuring the total pressure; pos. 3-static pressure measurement fitting; pos. 4-gas supply tube to the working chamber of the prototype; pos. 5-electron selection grid.

![Gas section of the experimental prototype of the first AMT accelerator system](image)

**Figure 2.** Gas section of the experimental prototype of the first AMT accelerator system

The mass gas consumption required for successful plasma generation is significantly lower than the sensitivity limits of the measuring equipment installed outside the vacuum chamber. Therefore, it is advisable to postpone the measurement of gas-dynamic quantities in the vacuum space, because the speed of gas leaving the pipeline in an area of low pressure are 300-500 m/s. This level of gas velocities is sensitive for the pressure gauge membrane. The accuracy of measuring values with a Pitot tube can reach 1% of the true value [3].

The diagram of the first AMT accelerator system is shown in fig. 3. The principle of operation is based on plasma generation (pos. 2, fig. 3) in the gap by an ultrahigh frequency electromagnetic field, plasma polarization by a constant or pulsed potential difference (PD) with the separation of the electron region (pos. 4) and the ions region (pos.3). The ions are accelerated by the RP and ejected outside the AMT through a perforated metal plate covered with a dielectric (pos. 6). This creates a reactive force. In figure 3 positions are indicated: 1-microwave generator; 2-plasma generation region; 3-ion region; 4-electron region; 5 -a positive electrode PD in the dielectric; 6 –negative electrode PD in the dielectric; 7 –neutralizer grid; 8 –membrane dielectric separating the fields of electrons and ions; 9 –flow of ions; 10 –the flow of neutral gas; 11 –supply of neutral gas in AMT.
The determination of the ionized gas jet current was based on assumptions:
1. The number of ions is equal to the number of electrons, i.e. only the first ionization potential of the molecule is overcome;
2. A microampermeter included in the chain between the grid installed in the electron region and the grid of the neutralizer shows the number of neutralized nitrogen molecules.

The flow rate was determined by measuring the surface temperature of the screen at regular intervals with the Testo 875-1i thermal imager. According to the stated characteristics, the sensitivity of the thermal imager is 0.05 °C. The screen is a rectangular sheet of fluoropolymer with an area of 47.36 cm² and a mass of 0.397 gr. The screen on the side of the thermal imager lens is covered with graphite paint. The distance from the neutralizer grid to the screen was 3 cm.

For rice, 4 shows the location of devices and systems in the vacuum chamber. In the figure, the positions are indicated by: pos .1-calorimeter; pos. 2 - prototype of AMT; pos. 3-pulse source of PD; pos. 4-thermal imager.

During the experiment, thermography of the calorimeter surface was performed for each type of exposure. There were 6 thermograms for each energy impact. Thermograms were taken at intervals of 15-20 seconds. Thus, for each impact, there are 15 power measurements, for which the average value is output.

Step feed (fig. 5) energy assumed:
1. Determination of the power of the gas jet (W_{GAS}) flowing from the working chamber of the prototype without microwave and PD;
2. Determination of the power of the gas jet (W_{GAS}+W_{mv}) flowing from the working chamber of the prototype with microwave, without PD;
3. Determining the power of the jet (W_{GAS}+W_{mv}+W_{PD}) flowing from the working chamber of the prototype with microwave and PD.

The calorimetric method allows you to see the flow power in the final States. To determine the contribution of each influence to the flow energy, it is necessary to determine the difference in the jet energy at each stage.
In this paper, the authors were interested in the value of the ionized gas velocity after the PD feed. The contribution of PD to the kinetic energy of the jet can be determined by the formula:

$$W_{PD} = W_{GAS} + W_{mv} + W_{PD} - W_{GAS} + W_{mv}.$$  

(1)

Given the transition of the entire kinetic energy of the accelerated PD of the ionized gas to the thermal energy of the calorimeter, the true expression:

$$\frac{m_{i} \cdot v^2}{2} = W_{PD},$$  

(2)

where $m_{i}$ is the mass consumption of ions. This value is determined by the value of the beam current:

$$m_{i} = \frac{M \cdot I}{N_{A} \cdot e},$$  

(3)

where $M$ – molecular weight; $I$ – current determined by the microammeter (fig. 3); $N_{A}$ – Avogadro number; $e$ – electron charge.

The thermodynamic state of a calorimetric load of mass $m$, uniformly heated to temperature $T$, is described by the expression [4]:

$$W = c \cdot m \cdot \frac{dT}{dt} + H \cdot (T - T_0),$$  

(4)

where $c$ – is the specific heat capacity of the load; $H$ – is the heat transfer coefficient; $T_0$ – is the ambient temperature.

Since the tests are performed under vacuum conditions and the values of the realized temperatures do not imply intense radiation, the second term in the formula (4) can be neglected.

4. Research Results

According to the pressure gauges ($P_1$=600 Pa, $P_2$=450 Pa, $P_3$=200 Pa) and the equilibrium pressure in the vacuum chamber of 48 Pa, the mass flow of nitrogen was obtained through the working chamber of the prototype AMT. It was 2.6 mg/s.

A calorimetric study of the power of the nitrogen stream flowing out of the AMT prototype showed an average power of $W_{GAS} = 1.021 \cdot 10^{-4}$ W. The supply of microwave energy increased the jet energy to $W_{GAS+mv} = 1.248 \cdot 10^{-3}$ W. Turning on the PD increased the power to $W_{GAS+mv+PD} = 1.595 \cdot 10^{-3}$ W. In contrast to the previous stages of energy supply, in the latter case, the average temperature of the calorimeter continuously increased during the entire time of measurements.

In fig. 6 shows the evolution of the heat spot on the screen when a pulse PD is applied with a voltage of 165 V. the total time for measuring temperatures is 75 seconds. A temperature scale of 20 to 24 °C is selected for display.

For comparison, in fig. 7 shows a heat spot in the absence of PD, but with gas and microwave plasma generation. To display the selected temperature scale from 20 to 24 °C. The time of measurement is 60 seconds.

In fig. 8 shows the evolution of the heat spot when only gas flows out of the prototype cavity. The measurement time is 99 seconds. The mass flow rate of nitrogen -2.6 mg/s.
The current recorded by the microammeter was 2.2-2.5 mA, which according to the formula (3) corresponds to the mass flow rate of the ionized gas $5.8 \cdot 10^{-7} - 7.3 \cdot 10^{-7}$ mg/s. According to the formulas (1) and (2), the speed of the ion jet was 30.81-34.45 km/s. The Theoretical jet thrust of such a device is 0.02-0.022 microns. The total power consumption of the prototype of the first AMT accelerator system was 4 watts.

5. Discussion of results

Verification of the obtained value of the ion flow rate was performed using classical formulas. The velocity of the ion can be determined using the kinetic energy acquired by the ion as it passes through the space between the electrodes [5]:

$$v_i = \sqrt{\frac{2eU}{m_i}}.$$  \hspace{1cm} (5)

At a voltage at PD $U=163$ V, taking into account the dielectric losses of the field strength in the insulators, formula (5) gives a speed value of 29.88 km/s. The Difference between the calorimetric values and those obtained by formula (5) is 925-4560 m/s.

The resulting discrepancy between the experimental and theoretical values of velocities can be explained by the accelerating action of the high-frequency gap. In part, this assumption is confirmed by the presence of a voltage level on the PD (in this prototype, 460-500 V), below which the current is not determined by the microammeter. When this level is reached or higher, the plasma is polarized and electrons move to the neutralizer grid. It is assumed that for the free movement of plasma in the working cavity of the prototype AMT, it is necessary to increase the field strength of the PD until it exceeds the field strength in the gap of the microwave generator grids. Next, the jet of ions accelerates in a mixed electric field: the Lorentz forces of the alternating and constant fields act on the charge. This question has not been studied separately, its solution may lie in the region of gap acceleration of ions, when the cavity between the PD electrodes is considered as a cylindrical volume resonator.
The concentration of charged particles does not depend on the voltage at the PD electrodes, since the electrodes do not participate in plasma generation. The percentage of ionization depends only on the mode of operation of the microwave generator.

The question of a significant increase in thermal power in the case of switching on microwave plasma generation, without the presence of PD, remains unexplored (fig. 7). In this case, you can make assumptions:
1. The increase in energy flow is provided by the neutral gas heated in the microwave gap;
2. The growth of the energy flow is provided by the accelerating action of a low-pressure microwave discharge.

The first assumption is confirmed by intensive heating of the capacitive microwave gap grids during plasma generation. In fig. 9 presents the types and images of the prototype AMT only when applying gas, when gas and microwave and gas supply, microwave and PD.

Figure 9. Increase in the surface temperature of the net of the neutralizer with a step-by-step supply of energy effects

The internal energy (in W) of an arbitrary amount of real gas (van der Waals gas) can be represented through the thermodynamic parameters of the gas [6]:

\[ c_v T \frac{\dot{m}}{M} - \frac{\alpha \cdot \rho \cdot \dot{m}}{M^2} = P, \]  

(6)

where \( c_v \) – is the isochoric heat capacity of the van der Waals gas.

Then, for the case of \( P = W_{\text{GAS+}} - W_{\text{GAS}} \) and nitrogen consumption of 2.5 mg/s, the gas temperature after passing the microwave discharge should increase by 0.6 °C.

The second assumption is based on the following: the gas temperature during the passage of the microwave gap changes slightly, the jet speed increases according to the formula (2) for the case of \( P = W_{\text{GAS+}} - W_{\text{GAS}} \). Then the gas velocity should be 29.603 m/s.

According to the value of the microwave transistor gain given by the manufacturers in the technical description (MRF 2841 transistor), which is 9.5 dB, you can estimate the voltage at the electrodes microwave gap. It is 17.9 V. For the case of motion of a charged particle in an alternating electric field of the microwave gap, the equation can be written:

\[ u_j = \left( \frac{e \cdot U}{2 \cdot \pi \cdot f \cdot m_j \cdot h} \right) \cdot \left( \cos x_0 - \cos x \right), \]  

(7)

where \( U \) - is the amplitude value of the voltage at the microwave gap electrodes; \( f \) is the frequency of the field (determined by the spectral analyzer, in the 600 MHz prototype); \( h \) is the gap value; \( x_0 \) is the phase of the electron’s flight into the gap.

The solution of equation (7) gives the value of the ions velocity at the exit from the gap -32.558 m/s.

6. Summary and conclusions

The article presents the results of the authors’ work in the field of engine building for small spacecraft. The authors developed and presented a prototype of the first accelerating system of an ion microjet thruster with microwave plasma generation in a capacitive emitter, followed by ion acceleration by a
constant potential difference. According to the results of calorimetric measurements, the energy of the ionized gas was obtained. The results of theoretical processing allow us to assume the presence of additional acceleration of charged particles in the discharge gap and the cylindrical resonator formed by flat electrodes of a constant potential difference. The mass flow rate of ions involved in electrostatic acceleration is many orders of magnitude lower than the mass flow rate of the gas. The energy consumption of the prototype was 4 W for all systems, a thrust of 0.02-0.022 microns was implemented, the ion velocity was 30.81-34.45 km/s with a pulse voltage on the electrodes of a potential difference of 165 V.

References
[1] Vavilov I S, Lukyanchik A I, Yachmenev P S [and others] 2018 Dilatometric Microdrive of small spacecraft with resonant microwave accelerator Omsk Scientific Bulletin 4 pp 36-41
[2] Hemminger W, Höhne G IOP Calorimetry: Fundamentals and Practice 1984 (Basel: Verlag Chemie GmbH) 310
[3] Milne-Thomson L M Theoretical Hydrodynamics 1960 (London: Macmillan and Co. LTD) 678
[4] Hamadulin E F Methods and means of measurement in telecommunication systems 2014 (Moscow: Yurayt) 365
[5] Sivukhin D V Electricity 2004 (Moscow: Fizmatlit) 680
[6] Sivukhin D V Thermodynamics and molecular physics 2005 (Moscow: Fizmatlit) 544

Source of financing
The research was carried out at the expense of a grant from the Russian science Foundation (project no.19-79-10038).