Determination of the thrust of an ion thruster by the aerodynamic method of double angle (AMαβ-method)

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Abstract. This paper presents the results of an experimental study of the jet thrust of a mixed jet of neutral and ionized nitrogen flowing from the working chamber of an experimental sample of an accelerator ion thruster into a vacuum space. The main method of the study was the aerodynamic double angle method (AMαβ-method). The method of determining low thrust and the design of the stand for the implementation of the AMαβ-method are proposed. The object of research is a prototype of an accelerator two-phase ion thruster with a solid-state microwave plasma generator and a toroidal resonator. The study showed that a 2.5 W microwave generator together with a 2.5 W accelerating potential difference voltage source with a nitrogen consumption of 0.05 -1 mg/s can increase the speed of the working gas by 2.3 times. The jet thrust, according to the test results, was 1-3.6 μN. It is shown that the thrust components (the gas-dynamic component, the ion component of a high-frequency discharge, the ion component of a glow discharge) have different levels depending on the mass flow rate of the gas.

1. Introduction
The work is published as part of a large project to create an accelerator ion thruster with low energy consumption. On the basis of the laboratory «Micro-traction propulsion systems of small spacecraft» Omsk State Technical University has developed a prototype of an accelerator two-gas ion thruster with an energy consumption of 5-10 W. The prototype implements stepwise acceleration of the microwave plasma in a high-frequency capacitive gap (diffusion of ions from the discharge gap), preliminary acceleration in an ion-optical system with a constant potential difference and acceleration in an alternating electric field of the gap of a toroidal resonator.

During the implementation of the project, the authors needed to develop methods for determining the speed of an accelerated ionized jet, the pressure force of the jet, the mass flow rate of the working fluid, the ion current, the electronic and ionic temperatures of plasma components, etc. Calorimetric and aerodynamic methods were used to determine the gas-dynamic parameters of the jet. The methods are chosen based on the constructive simplicity and the minimum of electronic components. The aerodynamic methods are implemented in two versions: resonant and double angle method. This paper presents the results of determining the thrust force of a jet flowing out of the working volume of an ion thruster by the aerodynamic double angle method (AMαβ-method).

The reactive force of an ion thruster with an energy consumption of less than 10 W is insignificant compared to the gas-dynamic force of a neutral gas entering the discharge chamber. It is extremely important to realize a low flow rate of the working fluid, since the percentage of ionization in high-
frequency or smoldering discharges does not exceed 0.1%. Gas consumption above 0.5 mg/s is not acceptable, because the ionic component of the thrust is completely lost in the gas-dynamic component. Low flow rates and low pressure of the ion jet significantly limit the constructive variety of methods for recording these effects. Currently, work in the field of low-watt ion thrusters with RF or microwave discharge is not carried out on a wide front. A search of open sources showed that the lower power limit was reached in the MMIT ion thruster [1]. The power of the sample is stated to be 8 W. The thrust is: on argon - 0.217 mN, on xenon - 0.392 mN. The largest number of authors works in the power range of 13-15 W. The MiDGIT xenon thruster produces jet thrust in the range of 0.25-0.48 mN with an energy consumption of 13-18 W [2]. The MRIT argon thruster [3] generates an ion thrust of 1.45-59 μN at an energy consumption of 13-15 W. The Japanese xenon ion thruster μ1 implements a thrust of 0.297 mN at a power consumption of 15.1 W [4, 5]. In the above publications, there is no information about whether the specified thrust values are the total thrust of the thruster (static thrust + gas-dynamic thrust of the neutral gas component + electrodynamic thrust of the ionic gas component) or this is the level of the ionic component only. Also, not all publications present the level of neutral gas consumption. The level of force action of the jet in some cases does not exceed the level of errors of the measuring equipment. For example, the lever stand for measuring the total thrust of the thruster, presented in [6], is designed to determine the thrust in the range of 100 μN - 1 N. The design is equipped with a conventional suspended pendulum lever attached to a balancing mechanism that converts the horizontal deviations created by the working thruster into an enhanced vertical movement of the secondary lever. The gain level is changed by adjusting the location of one of the reference points connecting the system. The reaction of the system depends on the relative values of the restoring moments created by the displaced mass of the thruster and the torsional hinges connecting the elements of the balancing mechanism. The displacement is measured using a non-contact optical linear gap displacement sensor. The sensitivity of the stand is 50 μN. The test bench was used to determine the thrust of a CHT xenon plasma thruster with an energy consumption of 90-185 W and a thrust of 3-6 mN [7-9]. The consumption of xenon was up to 1 mg/s. The thrust realized by ion thruster with an energy consumption of up to 10 W is in the region of up to 10 μN. Accordingly, the bench methods for determining the values of this level should correspond to this level. The main requirements include the simplicity of the mathematical apparatus, a minimum of rubbing surfaces, a minimum of transfer links.

As part of the research of the prototype of the accelerator ion thruster, in terms of determining the total jet thrust of a mixed jet (neutral gas component + ionized gas component), an aerodynamic method with a double angle (dewatering angle + measurement angle) of deflection of the sensor element was proposed and developed.

2. Problem statement
To conduct experimental research, a prototype of an accelerating microwave ion thruster with an energy consumption of less than 10 W was developed and manufactured. The prototype implements the concept of stepwise acceleration of an ionized gas in the high-frequency gaps of a plasma generator and a toroidal resonator (Fig. 1). The intermediate accelerator is a three-grid ion-optical system with a potential distribution on the grids: +200 V, 0 V, -1100 V. The working medium in the tests was nitrogen.

Figure 1. The appearance of the prototype of a microwave ion thruster and a demonstration of its operation in a vacuum chamber.
In this part of the work, the authors investigated the power characteristics of an accelerated jet of ionized nitrogen of a prototype microwave ion thruster. The authors proposed the concept of aerodynamic determination of the thrust of an ion thruster by the method of two angles. One angle was set by the tester and served to compensate for the weight of the sensor element, the second angle was the measured value.

To determine the thrust force of the prototype jet, it was necessary to solve the following tasks:

1. To develop the concept of an AMaß-method for measuring the thrust of an ion thruster and to make a stand;
2. Conduct vacuum experimental studies with different gas flow rates and at different compensation angles in order to determine the deflection angle of the sensor element of the stand. Determine the value of the reactive force.

3. Theory

In the framework of the authors' early work with thrusters running on "cold" and "hot" gases [10], a simple method for determining the pulse of a gas jet flowing into a vacuum space was proposed (Fig. 2).

![Figure 2. Device for measuring the thrust of a thruster](image)

1 – a thruster; 2 – a translucent mirror; 3 – a coordinate system; 4 – a laser; 5 – a beam; 6 – a video recording device

When the working fluid is fed into the thruster 1, the latter creates a thrust $P$, which deflects the translucent mirror 2 by an angle $\alpha$, justified by the equality of the moments of gravity and reactive thrust. The beam of the laser 4, mounted on the axis of the thruster, is reflected from the mirror and falls on the coordinate system 3. When the mirror deviates from the initial position, under the action of the thrust force, the reflected beam falls on the coordinate system at the position of point $N$.

$$A = \arctg \left\{ \frac{\sqrt{L^2 + H^2 - 2HR - L}}{H - 2R} \right\}, \quad (1)$$

where $L$ is the distance from the point of attachment of the mirror to the laser; $H$ is the distance from the laser to the point of incidence of the reflected beam; $R$ is the distance from the point of application of the thrust force to the point of attachment of the mirror.

Applying the expression (1), the thrust force $P$ can be calculated as:

$$P = G \tan(A) = G \left( \frac{\sqrt{L^2 + H^2 - 2HR - L}}{H - 2R} \right), \quad (2)$$

where $G$ is the weight of the mirror.

To determine the value of $H$ in the vacuum chamber, the stand is equipped with a video recording device with the ability to display images on the monitor.

The problems of the method regarding the registration of ion thrust are the large mass of the deflected screen. Reducing the mass by using less dense materials leads to a loss of structural rigidity and the occurrence of parasitic vibrations from the operation of the vacuum pump of the laboratory vacuum chamber.
To increase the sensitivity of the stand, it was proposed to introduce a second angle, measured from
the vertical.

Figure 3 shows a 3D model of the measuring part of the stand.

![Figure 3. Measuring part of the stand for the AMaß-method.](image)

1 – a rotary screen (in experiments, the screen material is expanded polystyrene, weight 0.7±0.05 gr.,
the position of the center of gravity from the thread is 72 mm, the position of the center of pressure
from the thread is 80 mm); 2 – a thin thread (in experiments – a fishing line, ø 0.05 mm); 3 – a support
of the measuring part; 4 – a rotary element; 5 – a support with a scale for setting the angle \( \beta \); 6 – a rotary
element with a scale (pos.7) for determining the angle \( \alpha \); 8 – the plane of setting the verticality of the
axis; 9 – the plane of the angle \( \alpha \); 10 – the indicator arrow for determining the angle \( \alpha \); 11 – the indicator
arrow for setting the angle \( \beta \).

Figure 4 shows the implemented stand assembly with an adjustment tripod.

![Figure 4. A stand for the implementation of the AMaß method for measuring the thrust of an ion
thruster](image)

The force of the jet is determined by the expression:

\[
P = m \cdot g \cdot \sin \alpha \cdot \sin \beta \cdot \frac{L}{H}
\]

where \( m \) is the mass of the rotating screen; \( g \) is the acceleration of gravity; \( L \) is the distance from the
axis of rotation of the screen to its center of gravity; \( H \) is the distance from the axis of rotation of the
screen to the center of pressure.

During the tests, the following drawback of the stand was revealed: a decrease in the angle \( \beta \) (the
angle of deviation of the axis of rotation from the vertical position) should increase the sensitivity of
the stand to small jet thrust and, accordingly, the value of the angle of rotation \( \alpha \) should increase at a
constant level of jet pressure. Practice has shown that ensuring the vertical position of the axis requires
additional thread tension to compensate for the torque created by the mass of the screen. Accordingly,
at low \( \beta \), the jet force is counteracted not only by the moment of gravity, but also by the torsion
moment of the stretched thread.
At step loading of the prototype of the ion thruster ("0"→"1"→"2"→"3") according to the readings of the stand, it is possible to distinguish individual components of the thrust. The state " 0 " means that there are no effects on the calorimeter and its steady-state readings in vacuum. State " 1 " → feed of the working fluid. State " 2 " → switching on the microwave generator. State " 3 " → switching on the ion-optical system.

The scheme of the experimental setup is shown in Fig. 5.

![Figure 5. Test scheme for determining the thrust of an ion thruster](image)

1–a cylinder with a working body; 2–a gearbox; 3–an electropneumoclap; 4–a throttle; 5–a flow meter; 6–a transition coupling; 7–a pressure gauge; 8–a vacuum chamber; 9–an ion thruster; 10–a thrust measurement stand.

The measurements are made according to the sequence:
1. Assemble the circuit (Fig. 5).
2. Install a traction measurement stand in the vacuum chamber. The sensing element of the stand is located 20-50 mm from the external grid of the toroidal resonator of the ion thruster;
3. Install a webcam in the vacuum chamber, so that the scale of the traction measurement stand is visualized on the personal computer monitor;
4. Connect the electrical contacts of the microwave generator and the ion-optical system to the power sources and check them;
5. Vacuum the system until a pressure of less than 18 Pa is reached;
6. Fix the initial position of the indicator arrow (mode "0");
7. Feed the working fluid (nitrogen) into the working cavity of the prototype ion thruster. Achieving a steady flow rate of the working fluid according to the flow meter readings [11]. Fix the new position of the indicator arrow (mode "1");
8. Turn on the microwave generator. To achieve the appearance of a high-frequency discharge. Fix the new position of the indicator arrow (mode "2");
9. Apply voltage to the grids of the ion-optical system. Fix the new position of the indicator arrow (mode "3");
10. Record the readings of the indicator arrow and the flow rate of the working fluid. At the end of the experiment, turn off and start the vacuum system;
11. Perform a theoretical analysis of the obtained data according to the formula (3).

Measurements were carried out at the angles $\beta =2^\circ$ and $\beta =3^\circ$. As a result of studies of the thrust of the prototype ion thruster by the resonant aerodynamic method, the value of the reactive thrust was obtained. It was $0.141\pm0.188\ \mu N$. The mass flow rate of neutral gas was $0.107\ \text{mg/s}$. The steady-state voltage between the grid and the cathode was $904\ \text{V}$ at a current of $124\ \mu\text{A}$.

4. Results experiments

According to the scheme (Fig. 5), the pressure force of a mixed gas jet was studied by the AMaß method. The results of the experiment with the prototype of the ion thruster are presented in Table 1. The nominal voltage on the grid and cathode of the ion-optical system is -1095 V. The supply voltage of the microwave generator is - 6 V, the current is - 0.39 A.
The velocity of the mixed gas flow (average velocity) is determined by the formula:

\[ u = \frac{P}{\dot{m}}, \]  

(4)

where \( P \) is the thrust value according to the formula (3); \( \dot{m} \) is the mass flow rate of gas according to the flow meter.

In the table, 1 and 2 show the measurement results for the distances between the sensing element of the stand and the nozzle section of 50 mm and 20 mm. Potential distribution on the grids of the ion-optical system: +200 V, 0 V, -1100 V.

**Table 1.** Measured and calculated values within the AMaß-method (distance of 50 mm)

| \( \beta, \degree \) | \( \alpha, \degree \) | \( \dot{m}, \text{mg/s} \) | Thrust, P, \( \mu \text{N} \) according to the formula (3) |
|-----------------|-----------------|-----------------|-----------------|
| 3               | 0.3             | 0.3+0           | 0.3+0+0.2       | 0.565           | 1.815           | 1.815           | 3.024           |
| Steady-state voltage, V | Current between the grid and the cathode, \( \mu \text{A} \) | 1028 | 594 | 3.213 | 3.213 | 5.354 |

| \( \beta, \degree \) | \( \alpha, \degree \) | \( \dot{m}, \text{mg/s} \) | Thrust, P, \( \mu \text{N} \) according to the formula (3) |
|-----------------|-----------------|-----------------|-----------------|
| 3               | 0.6             | 0.6+0           | 0.6+0+0.0       | 0.672           | 3.629           | 3.629           | 3.629           |
| Steady-state voltage, V | Current between the grid and the cathode, \( \mu \text{A} \) | 1031 | 445 | 5.401 | 5.401 | 5.401 |

| \( \beta, \degree \) | \( \alpha, \degree \) | \( \dot{m}, \text{mg/s} \) | Thrust, P, \( \mu \text{N} \) according to the formula (3) |
|-----------------|-----------------|-----------------|-----------------|
| 2               | 0.2             | 0.2+0           | 0.2+0+0.1       | 0.214           | 0.807           | 0.807           | 1.21            |
| Steady-state voltage, V | Current between the grid and the cathode, \( \mu \text{A} \) | 1038 | 388 | 3.765 | 3.765 | 5.648 |

| \( \beta, \degree \) | \( \alpha, \degree \) | \( \dot{m}, \text{mg/s} \) | Thrust, P, \( \mu \text{N} \) according to the formula (3) |
|-----------------|-----------------|-----------------|-----------------|
| 2               | 0.8             | -               | 0.8+0          | 0.915           | 3.227           | -               | 3.227           |
| Steady-state voltage, V | Current between the grid and the cathode, \( \mu \text{A} \) | 1025 | 467 | 3.525 | - | 3.525 |

| \( \beta, \degree \) | \( \alpha, \degree \) | \( \dot{m}, \text{mg/s} \) | Thrust, P, \( \mu \text{N} \) according to the formula (3) |
|-----------------|-----------------|-----------------|-----------------|
| 2               | 0.1             | 0.1+0.1         | 0.253          | 0.403           | 0.807           | -               | 3.186           |
| Steady-state voltage, V | Current between the grid and the cathode, \( \mu \text{A} \) | 1063 | 404 | 1.593 | - | 3.186 |

– in the measurements, the "2" section was passed and the "3" section was immediately followed.

**Table 2.** Measured and calculated values within the AMaß-method (distance of 20 mm)

| \( \beta, \degree \) | \( \alpha, \degree \) | \( \dot{m}, \text{mg/s} \) | Thrust, P, \( \mu \text{N} \) according to the formula (3) |
|-----------------|-----------------|-----------------|-----------------|
| 2               | 0.3             | 0.3+0.4         | 0.049           | 1.21            | -               | 2.823           |
| Steady-state voltage, V | Current between the grid and the cathode, \( \mu \text{A} \) | 1049 | 306 | 24.851 | - | 57.984 |

– in the measurements, the "2" section was passed and the "3" section was immediately followed.
5. Discussion of results
As part of the study of the prototype of an accelerating two-gas microwave ion thruster, a simple method for determining the jet thrust of a mixed jet of the working fluid of the thruster was proposed. Based on the measurement results, diagrams are constructed (Fig. 6). A fragment with a thrust measurement is separately selected when the sensing element of the stand is located at a distance of 20 mm from the grid of the toroidal resonator. Figure 6a shows a diagram of the pressure forces of neutral gas and mixed gas on the sensor element of the stand, depending on the flow rate of the working fluid. It can be seen that with an increase in the gas flow rate, the ionic component of the thrust, as the thrust difference between the modes "3" and "1" tends to zero. This indicates the predominance of the gas-dynamic component of the thrust over the electrodynamic one. Also, this may mean a significant braking of the ionized flow in the gas cushion formed in the area between the sensitive element of the stand and the end of the thruster. At the same time, with the lowest gas consumption, the current between the grid and the cathode of the ion-optical system is the smallest (Fig. 6b). This may mean that the thrust is created largely due to the ions formed in the high-frequency discharge of the plasma generator, and not due to the secondary discharge ions between the grids of the ion-optical system.

**Figure 6a.** Summary graph of the dependence of the mass flow rate of the working fluid on the steady-state voltage and ionic thrust

**Figure 6b.** Summary graph of the dependence of the mass flow rate of the working fluid on the current and ionic thrust
Figure 6c. Dependence of the flow rate of the working fluid on the thrust

At a flow rate of 0.5-0.6 mg/s, an abnormal voltage drop is observed (Fig. 6 c) with an increase in the current between the grid and the cathode (Fig. 6 b). At the same time, an increase in the ionic component of the thrust is observed. This phenomenon may indicate that in this case, the increase in thrust is due to the ions of a secondary glow discharge formed between the cathode and the grid of the ion-optical system. With an increase in the mass flow rate of the working gas, the role of the secondary discharge increases and in the process of creating thrust, DC discharge ions become more important. At the same time, the level of the steady accelerating voltage decreases, the gas is heated due to the Joule-Lenz energy.

For comparison, the experimental resonant aerodynamic method showed a thrust level of 0.15-0.2 μN for a gas flow rate of 0.107 mg / s at a current between the cathode and the grid of 124 μA. The operating modes of the prototype ion thruster during the tests of the AMaß-and resonant aerodynamic methods are identical. The differences are in the level of flow of the working gas.

6. Conclusion

The article presents the results of work in the field of measuring the power characteristics of low-energy ion thruster for small spacecraft. The authors developed a stand and presented an aerodynamic double angle method for determining the reactive thrust of a prototype ion thruster with microwave plasma generation in a capacitive radiator, followed by ion acceleration by a constant potential difference. According to the results of the measurements, the thrust and velocity of the ionized gas were obtained.

The following conclusions can be drawn from the results of the experiments:

1. With an increase in the mass flow rate of the working fluid, the ionic component of the reactive thrust is completely "lost" in the gas-dynamic thrust. In high gas flow conditions (above 0.2 mg/s), the use of ion thruster is impractical;
2. The gas-dynamic thrust decreases with increasing distance from the nozzle section of the prototype ion thruster, which indicates a large angle of neutral gas atomization;
3. At low gas flow rates (less than 0.05 mg/s), the electrodynamic thrust prevails over the gas-dynamic one. The use of an ion-optical system increases the speed of the mixed gas by 2.33 times;
4. The level of ion thrust decreases slightly with increasing distance from the nozzle cutoff and is in the range of 0.4-0.45 μN, which indicates the focusing effect of the ion-optical system and the toroidal resonator grids.

In the case of a close location of the sensor element of the stand to the nozzle section of the prototype, the effect of acceleration of the charged component in the high-frequency gap of the emitter is
noticeable. This component also has a large spray angle, but is more focused than the gas flow. This is indicated by the tests of the prototype on the stand of the ion-tag (time-of-flight) method, when the ion sensors "triggered" the ignition of the discharge at a distance of 50 mm with a toroidal resonator and at a distance of up to 100 mm –with a cylindrical resonator (the resonator with a diameter of 140 mm is removed).

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