

# Experimental studies of arcjet thruster in pulsed mode of operation for corrective propulsion systems of small spacecraft

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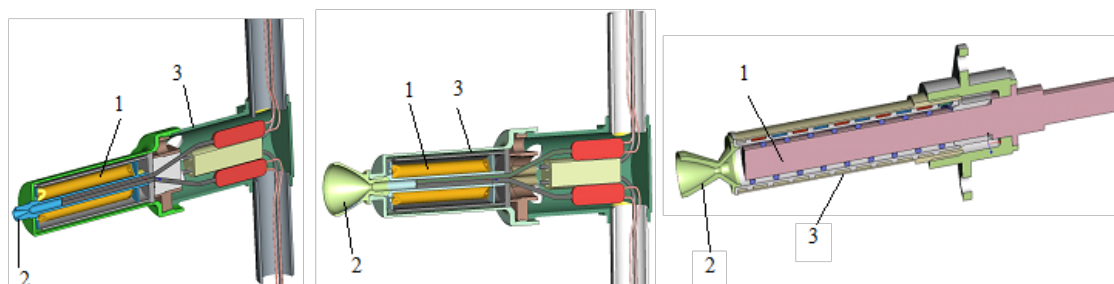
**Abstract.** The paper presents the results of experimental studies of an arcjet thruster in pulsed mode of operation on nitrogen with a thrust value of up to 32 mN and energy consumption of up to 30 watts. The pulse mode of operation of the arcjet thruster is provided by the developed power source. At measured values of temperature at the nozzle and pressure in the arc chamber of the engine in a pulsed mode of operation define the basic characteristics of gas-dynamic functions of gas flow. The forecast of the achieved values of the specific impulse when using ammonia as a working fluid is carried out

## 1. Introduction

There are many types of micro-motors for corrective propulsion systems (CPU) of small spacecraft (SSC), which differ in the way energy is transferred to the working body. Due to the structural simplicity, electric heating thruster (EHT) are widely used, where the power plant is an electric resistance element.

Efficiency EHT depends on the supplied power to the heating elements, the duration of a single inclusion, structural perfection, launch method etc. In this regard, specific impulse EHT that determines its effectiveness has its limits, associated, primarily, with the available capacity of the onboard power system of SSC.

Created ammonia EHT with a wire heating elements with a thrust of 30 mN is used in a number of mass from 30 to 120 kg Specific impulse EHT with such power consumption 60 W does not exceed 230 s (figure 1) [1].



**Figure 1.** EHT.

1-heating element; 2-jet nozzle; 3-housing



Further improvement of the CPU with EHT is associated with the creation of CPU with arcjet thruster (AT) with low energy consumption and high specific impulse thrust.

In AT, the element of electrical resistance, the Joule heat generator, is an electric arc that occurs between the electrodes in the flow of the working gas. The thermal energy of the electric arc without intermediate surfaces is transferred to the working body, which leads to an increase in its temperature and decomposition. From the point of view of efficiency of energy exchange AT differs from EHT in absence of the intermediary – the heat exchanger.

Currently, most AT developments have a high power consumption (500-1000 W) and can be used on SSC of significant mass from 200 kg and more [2-3].

SSC weighing up to 200 kg are characterized by the presence of a power supply system with limited characteristics of the generated power in the interests of the functioning of the AT. This puts forward an urgent task to reduce the energy consumption of AT in order to reduce the starting mass of the SSC.

For SSC weighing up to 200 kg, the following results were achieved on:

- ammonium AT VELARC developed in Germany with a specific impulse from 350 to 520 s, thrust from 27.5 to 35 mN and a power consumption from 240 to 375 watts [4];
- hydrazine AT Sagami-III developed in Japan with a specific impulse from 420 to 480 s with the pull rod 47 mN and a power consumption from 285 to 300 W [5];
- ammonium AT Mini LPATS with a specific impulse of from 360 to 470 s, the thrust from 30 to 51 mN and a power consumption of 250 watts [6];
- nitrogen AT developed in Russia with a specific impulse of 250 s, a thrust of 38 mN power 160 W [7].

For SSC weighing up to 100 kg, the following results were achieved on:

- helium AT operating in pulsed mode was developed in the US with a specific impulse of 180 s, a thrust of from 2.8 to 4.8 mN in power consumption from 100 to 200 watts [8];
- nitrogen AT developed in Japan with a specific impulse of up to 100 s with a thrust of 1.5 to 2 mN with power consumption from 1 to 5 W [9].

Low thrust engines are presented for the SSC to 100 kg leads to lower fuel consumption and as a consequence a great time generation, which increases during the orbital maneuver, in addition the pulse AT developed in the United States has high consumption peak discharge power over 100 kW, which leads to increased wear of the electrodes.

Reducing power consumption and reducing the time of the orbital maneuver of the SSC is associated with the creation of AT with a pulsed mode of operation of increased thrust.

## 2. Problem statement

The task of experimental studies of AT in pulsed mode of operation on nitrogen with increased thrust and energy consumption from 5 to 30 watts.

The aim of the experimental studies were the following tasks:

- measurement of the achieved temperatures of the working fluid on the nozzle section;
- measurement of the achieved working fluid pressure in the flow line before the AT;
- calculation of the main characteristics of AT in the pulse mode of operation using a mathematical model describing the gas-dynamic functions of the gas flow;
- visual control of processes of functioning of AT;
- prediction of the achieved specific impulse thrust AT when using ammonia as a working fluid.

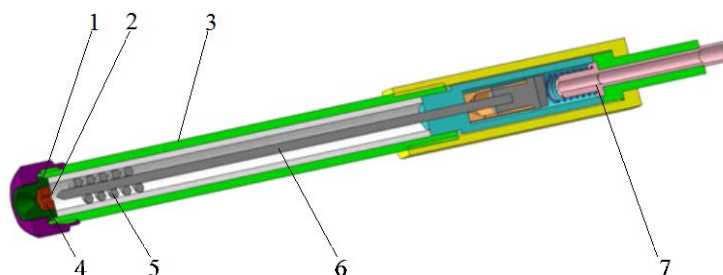
## 3. Theory

Calculation of the main characteristics of AT in the pulse mode of operation was carried out using a mathematical model describing the gas-dynamic functions of the gas flow presented in [7, 10].

During the experimental studies of AT in the pulse mode of operation, measurements of the working fluid temperatures at the nozzle section and the achieved pressure in the flow line were carried out.

Using the measured temperatures of the working fluid and pressures in the flow line AT were calculated basic parameters such as thrust  $P$ , specific impulse  $I_{sp}$ , pressure on the nozzle section  $p_n$ , the temperature of the working fluid in the chamber  $T_c$  and mass flow of the working fluid  $\dot{m}$ .

The object of the study is the mode of operation of AT for SSC. AT has a conical nozzle with a critical cross-section diameter  $d_{kr}=0.8$  mm and a nozzle cut diameter  $d_n=2.0$  mm (Fig. 2).

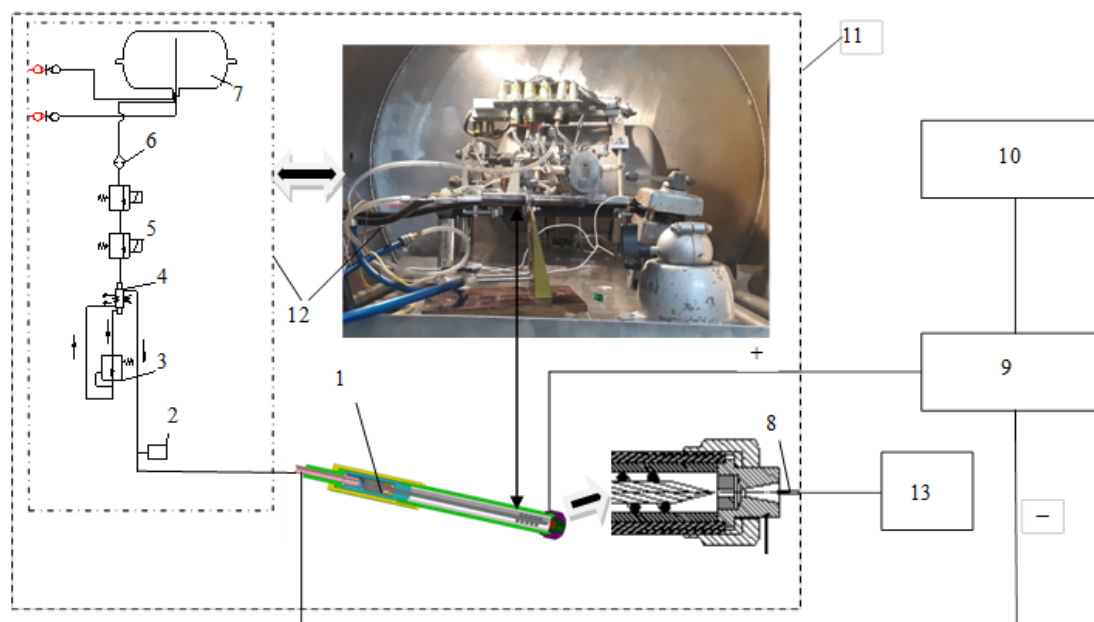


**Figure 2.** 3D model AT.

1 - jet nozzle; 2 - zone of the formation of pulsed discharges 3 - housing; 4 - anode (thoriated tungsten); 5 - shaper gas swirl; 6 - cathode (lanthanum tungsten); 7 - supply line of the working fluid

To carry out experimental studies of AT in the pulse mode of operation, a developmental sample of the CPU with an ETH and a control unit was used. Instead of the ETH and the control unit, the AT and the power supply were connected, providing a pulse mode of operation of the AT. The AT power supply was located outside the vacuum chamber due to the characteristics of the electrical components used.

The schematic diagram of experimental studies of AT in the pulse mode of operation is shown in figure 3.



**Figure 3.** Schematic diagram of experimental studies of AT in pulsed mode of operation.

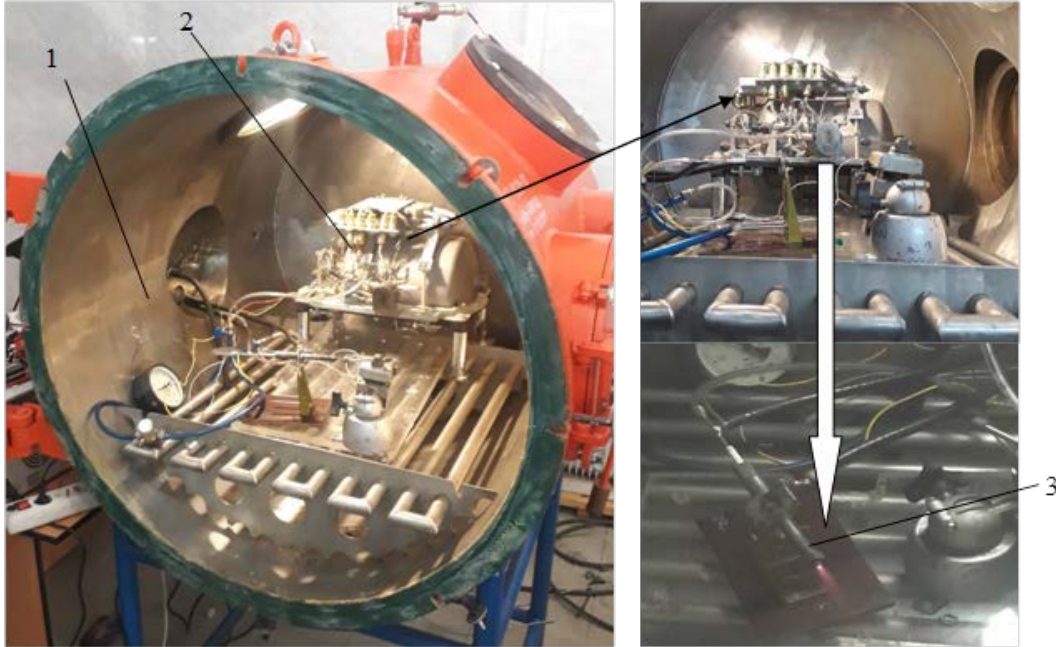
1-AT; 2-pressure gauge; 3-pressure regulator; 4-evaporator; 5-electrovalve; 6 – filter; 7-fuel tank; 8-thermocouple nozzle; 9 - power supply AT; 10-laboratory power supply; 11-vacuum chamber; 12-CDU; 13-temperature meter

The pressure value of the working fluid in the AT chamber was recorded using a pressure gauge installed before entering the AT.

The temperature of the working fluid at the nozzle section was recorded using a Cr/Al thermocouple with a measurement limit of 973 K.

To carry out experimental studies of AT in the pulse mode of operation, a power source was created that generates high-voltage multipolar pulses close to a rectangular shape. The power supply has galvanic isolation and a pulse output voltage of 1.1 kV with a frequency of 83 kHz and a pulse duration of 200 NS. The power supply operates in the power range from 5 to 30 W and voltages from 8 to 17 V.

For figure 4 shows an experimental setup for the study of AT in the pulse mode of operation.



**Figure 4.** Experimental setup for the study of AT in pulsed mode of operation.

1-chamber for the study of AT in a vacuum environment; 2-CPU; 3-AT in pulsed mode of operation

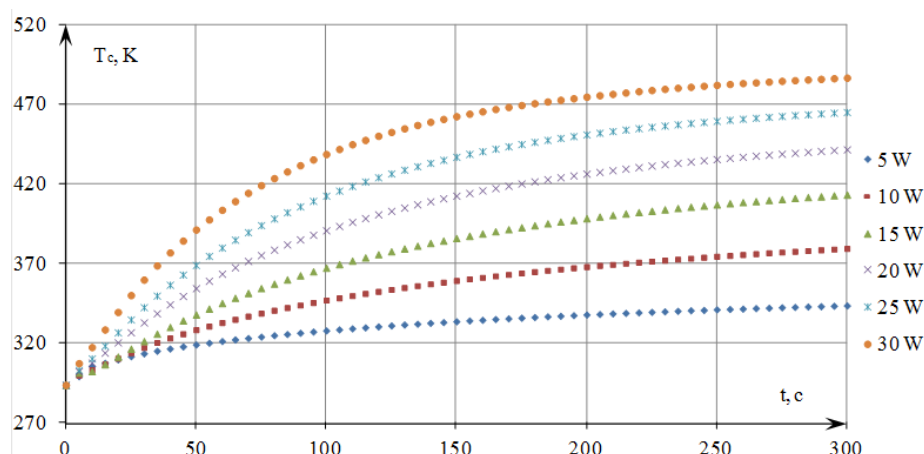
#### 4. Experimental results

Measuring the temperature of the working fluid on the nozzle section, as well as the pressure in the AT chamber was carried out during a single turn-on time AT, which was 5 min.

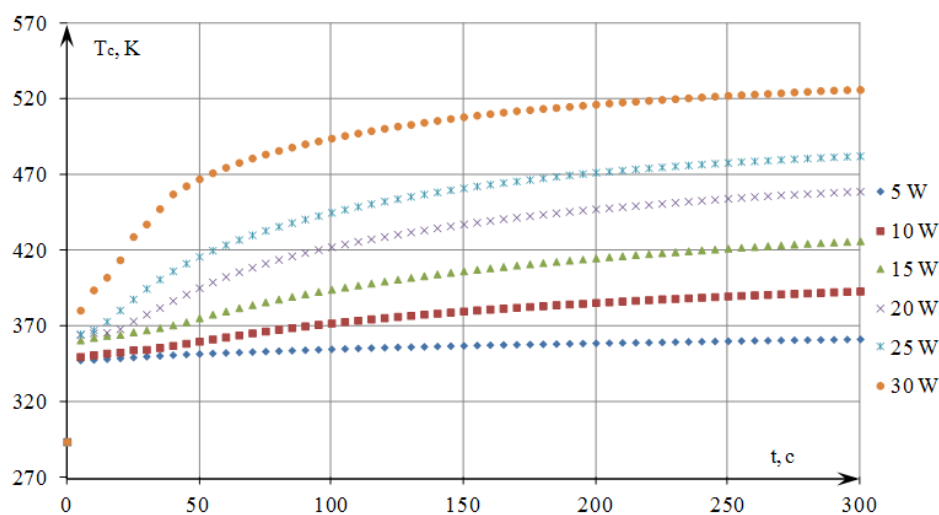
The temperature of the working fluid at the nozzle section was from 343 to 526 K at a power consumption of 5 to 30 watts.

The operation time of the AT operating in pulse mode was 10 hours. Inspection of electrodes and design AT did not reveal geometrical changes.

For figure 5-6 the dependences of the working fluid temperature on the nozzle section on the AT operation time are presented.



**Figure 5.** The temperature of the working fluid at the nozzle AT at a line pressure of 0.4 atm



**Figure 6.** The temperature of the working fluid at the nozzle AT at a line pressure of 0.3 atm

The results of AT studies in the pulse mode of operation in the form of measured temperature at the nozzle section  $T_c$  and pressure in the chamber of the pulse AT  $p_c$  and the design parameters are given in table 1.

**Table 1.** Experimental results and calculated parameters of AT in pulsed mode of operation.

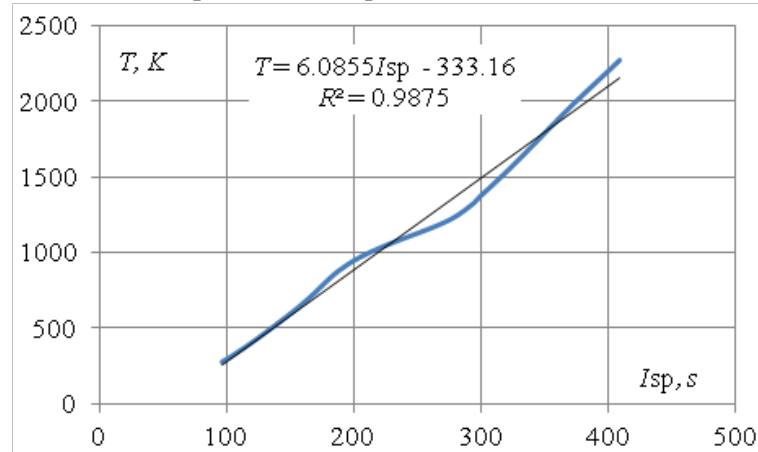
Working medium	Measured parameters			Design parameters				
	$P_c$ , kg/cm <sup>2</sup>	$T_n$ , K	$N_{at}$ , W	$P_c$ , kg/cm <sup>2</sup>	$T_c$ , K	$P_{sp}$ , s	$P$ , mN	$\dot{m}$ , mg/s
Nitrogen	0.3	361	5	0.004	1201	140	24.2	17.3
		393	10		1307	146		16.6
		426	15		1417	152		15.9
		459	20		1527	158		15.3
		482	25		1603	162		15
		526	30		1750	169		14.3
	0.4	343	5	0.006	1141	136	32.3	23.6
		379	10		1261	143		22.5
		413	15		1374	150		21.5
		441	20		1467	155		20.8

		465	25		1547	159		20.3
		486	30		1617	162		19.9

According to the results of experimental studies, the temperature of the working fluid in the AT chamber was determined by calculation, which ranged from 1141 K to 1750 K.

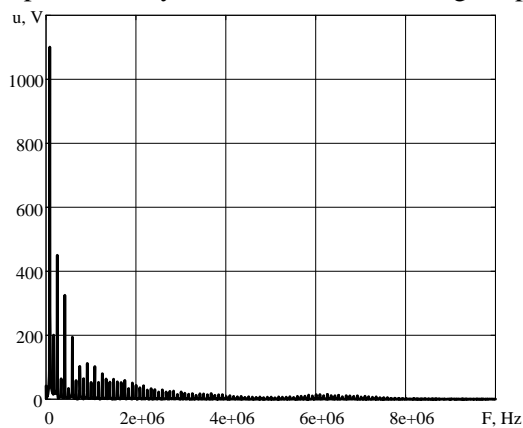
The obtained temperature of the working fluid in the AT chamber was used to predict the achieved specific impulse of the AT in the pulsed mode of operation using ammonia as the working fluid (figure 7) [11].

The achieved specific impulse of AT in the pulse mode of operation with the use of ammonia as a working was from 230 to 340 s at a power consumption of 5 to 30 W.

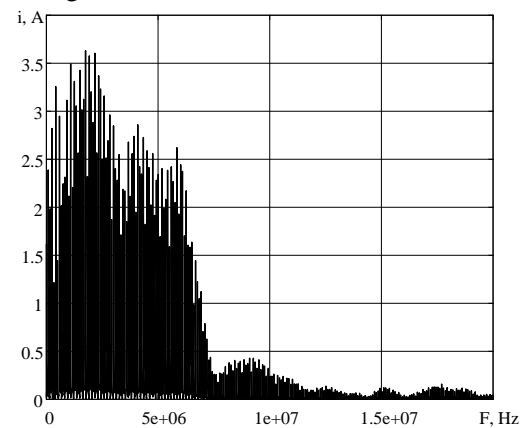


**Figure 7.** Calculated values of the specific thrust impulse of ammonia AT in the pulse mode of operation

Spectral analysis for current and voltage is presented in figures 8 and 9.

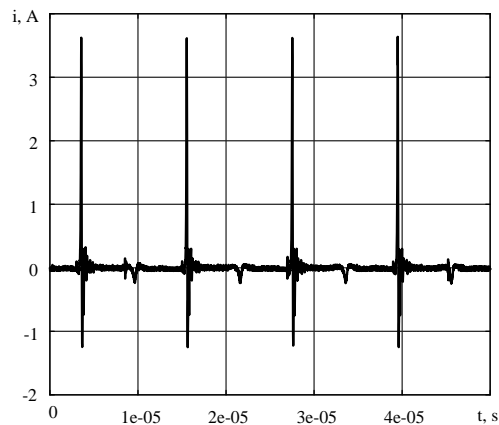


**Figure 8.** Spectral composition of AT supply voltage in pulse mode of operation

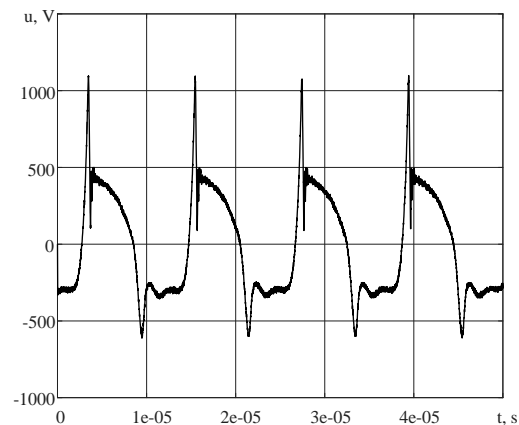


**Figure 9.** Spectral composition of the consumed current AT in the pulse mode of operation

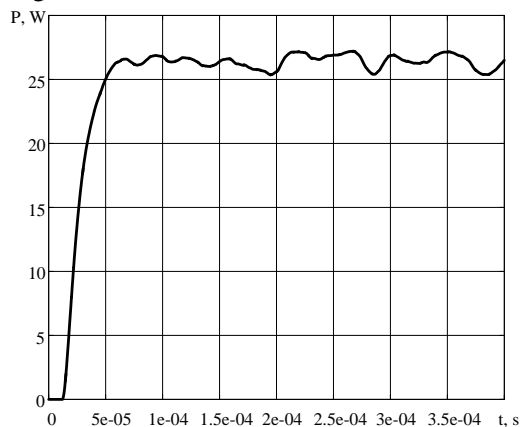
Figures 10 and 11 show the current and voltage waveform.



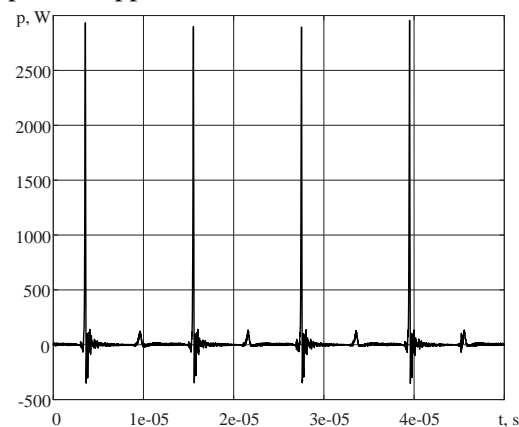
**Figure 10.** Instantaneous value of current consumption AT in pulse mode of operation



**Figure 11.** Instantaneous value of voltage on AT electrodes in pulse mode of operation



**Figure 12.** RMS value of AT power consumption in pulse mode of operation



**Figure 13.** Instantaneous value of AT power consumption in pulse mode of operation

## 5. Results and discussion

The studies of AT in the pulse mode of operation at power consumption from 5 to 30 W showed that the AT parameters are in the following ranges:

- temperature of the working fluid in the chamber at the entrance to the critical section of nozzle - from 1141 to 1750 K;
- specific impulse thrust - from 136 to 169 with;
- thrust AT - from 24.2 to 32.3 mn;
- the flow of the working fluid from 14.3 to 23.6 mg/s.

The achieved specific impulse of AT in the pulse mode of operation with the use of ammonia as a working was from 230 to 340 s at a power consumption of 5 to 30 watts.

Figures 8, 9 demonstrate that at the curve of the AT current and voltage consumption in addition to the fundamental harmonic, there are additional high-frequency harmonics of different amplitude and phase, and the spectrum itself consists exclusively of discrete frequency components.

The pulse periodic mode of the arcjet thruster is represented by a Fourier series containing some component with cyclic frequency  $f = \frac{1}{T}$  and harmonics which are arranged uniformly with frequencies  $k \cdot f$ , where  $k=2, 3, \dots$

Figures 10 and 11 show that at reaching a voltage positive half-wave of 1.1 kV, a gas breakdown occurs, caused by an increase in the current to 3.5 A.

At the maximum measured power consumption, the efficiency coefficient of the pulse source operating in a periodic mode was 82%.

## 6. Conclusion

The developed power supply with the output periodic pulse voltage allowed to reduce the power consumption of the AT and improve the stability of operation. The use of this type of power supply significantly reduces the size and weight. Due to the use of bipolar pulsed high-frequency voltage, the probability of starting and entering the AT operation mode tends to one. In addition, by controlling the frequency and fill factor after starting the AT, it is possible to change the discharge characteristics to reduce.

The results of the conducted researches testify to high efficiency of AT in the pulse mode of functioning at power consumption from 5 to 30 watts. The specific impulse of thrust up to 160 s and thrust up to 32.3 mN with a flow rate up to 23.6 mg/s allow to draw a conclusion about the expediency of using AT in SSC weighing up to 200 kg.

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