Experimental investigations of nitrogen arcjet thruster with control unit for small spacecrafts

V N Blinov, I S Vavilov, V V Fedynin, V V Shalay, P S Yachmenev and V I Ruban
Omsk State Technical University, 11, Mira Ave., Omsk, 644050, Russia

Abstract. The article presents the experimental study results of a nitrogen arcjet thruster prototype for small spacecrafts with a control unit, having thrust up to 38 mN and power consumption up to 160 W. As the result of the experimental studies, the measured values were obtained for the temperature at the nozzle exit and surface and for the pressure in the arcjet thruster chamber. Thanks to the measured parameters, the main characteristics of the arcjet thruster were calculated through gas-dynamic functions of the gas flow. Minimal values for power consumption were determined to ensure stable operation of the arcjet thruster. The validity of the proposed mathematical model was verified by visual detection of active nitrogen formation in a vacuum chamber.

1. Introduction
There exist studies and developments in the production field of a nitrogen arcjet thruster having power of less than 1kW [1-2]. For example, arcjet thrusters developed in China have power consumption of 1 kW, specific impulse 65 s and thrust from 30 to 50 mN. Moreover, there are arcjet thrusters with power consumption from 400 to 720 W and specific impulse from 150 to 300 s.
Such thrusters can be used in small spacecrafts (SSC) having the mass from 200 ...400 kg and more.
Power consumption decrease is relevant for SSC in a wide range of masses, since it results in arcjet thruster and SSC power supply system masses decrease. Moreover, a low-power arc discharge would increase the arcjet thruster lifespan by decreasing the electrodes wear-and-tear as they would operate at lower temperatures.
There is a nitrogen arcjet thruster with power up to 150 W developed in Japan for SSC having mass up to 100 kg. This arcjet thruster has specific impulse up to 270 s, thrust from 0.5 to 6 mN at power consumption from 2 to 20 W.
Such low thrust results in low fuel consumption and, consequently, in longer fuel use time. In case of fuel loads characteristic for SSC with the mass from 200 kg and more (for example, 6 kg), the fuel use time and, as a result, orbital maneuver time are 757 hours for 6 mN thrust.
Decreased orbital maneuver time for SSC can be achieved by developing an arcjet thruster with an increased thrust from 20 to 38 mN.

2. Problem statement
The article aims to experimentally study a nitrogen arcjet thruster prototype with a control unit having an enhanced thrust up to 38 mN and power consumption up to 160 W.
The following tasks are solved through experimenting:
• visual control of the arcjet thruster operation processes;
• measuring achievable temperatures at the nozzle exit and surface;
• measuring achievable pressure values in the arcjet thruster chamber;
• determining minimal values for the arcjet thruster power consumption to ensure its stable operation;
• calculating the main characteristics of the arcjet thruster, such as specific impulse, temperature in the arcjet thruster chamber, thrust and the working medium consumption in the arcjet thruster.

3. Theory
To estimate the main characteristics of the arcjet thruster, the use was made of the mathematical model including parametric dependences to calculate thrust $P_{AT}$ and specific impulse $P_{sp}$, temperature in the chamber $T_c$ and pressure at the nozzle exit $p_n$, through a gas-dynamic function of the gas flow [4, 5]:

$$ P_{AT} = P_c \cdot F_{th} \cdot K_T; $$

$$ K_T = \left( \frac{\lambda_n + 1}{\lambda_n} \right) \left( \frac{2}{k + 1} \right); $$

$$ P_{sp} = a_{th} \cdot K_{sp}; $$

$$ a_{th} = W_{th} = \sqrt{\frac{2k}{k + 1} \frac{R_T c}{M_g}}; $$

$$ K_{sp} = \left( \frac{\lambda_n + 1}{\lambda_n} \right) \left( \frac{k + 1}{2k} \right); $$

$$ q(\lambda_n) = \frac{F_{th}}{F_n} = \frac{W_n \rho_n}{W_{th} \rho_{th}} = \lambda_n \left( \frac{k + 1}{2} \right)^{(k-1)} \left( 1 - \frac{k - 1}{k + 1} \lambda_n^2 \right)^{(k-1)}; $$

$$ \tau(\lambda_n) = \frac{T_n}{T_c} = \left( 1 - \frac{k - 1}{k + 1} \lambda_n^2 \right); $$

$$ \pi(\lambda_n) = \frac{p_n}{p_{th}} = \left( \frac{k - 1}{k + 1} \right)^{(k-1)}; $$

$$ T_n = T_c \left( \frac{p_n}{p_{th}} \right)^{\frac{k - 1}{k}}; $$

where $K_T$ is a nondimensional thrust coefficient;
$K_{sp}$ is a nondimensional coefficient for specific impulse
$T_n, T_c$ is the gas temperature at the nozzle exit and in the arcjet thruster chamber, correspondingly;
$\rho_n, \rho_{th}, \rho_{th}$ is the gas density at the nozzle exit and in the arcjet thruster chamber, correspondingly;
$p_n, p_{th}$ is the gas pressure at the nozzle exit and in the arcjet thruster chamber, correspondingly;
$F_n, F_{th}$ is the area of the nozzle exit and the nozzle throat, correspondingly;
$W_n$ is the velocity of the gas flow at the nozzle exit;
$a_{th} = W_{th}$ is the gas flow velocity equal to that of sound at the nozzle throat;
k is the impact adiabat exponent for the used gas;
$R^*$ is a universal gas constant;
$M_g$ is a molar mass of the used gas;
$q(\lambda_n)$ is a relative area of the nozzle throat;
$\tau(\lambda_n)$ is a relative temperature of the nozzle exit;
$\pi(\lambda_n)$ is a pressure ratio at the nozzle exit;
λ_n is the ratio of the velocity at the nozzle exit to that of the gas flow at the nozzle throat.

The characteristic feature of the applied model is that one uses values $T_u$ and $p_i$ obtained in the experiments as design data, while the values $P_{at}$, $P_{wp}$, $T_e$, $p_a$ and that of the mass working medium consumption $\dot{m}$ were determined by calculation.

The study subject is an arcjet thruster for SSC correcting propulsion systems (CPS) with a conical nozzle having a throat diameter $d_{th} = 0.7$ mm and a nozzle exit diameter $d_n = 2.0$ mm (figure 1).

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**Figure 1.** Arcjet thruster prototype.
1, 5 – swivel nut; 2 – nozzle; 3 – casing; 4 – tube (corundum ceramics); 6 – collet; 7 – spring; 8 – anode (thoriated tungsten); 9 – swirler; 10 – cathode (lanthanated tungsten); 11, 13 – insulating insert (PTFE); 12 – working medium feedline

Pneumatic-hydraulic schematic for testing the arcjet thruster as a part of the performed CPS prototype in a vacuum chamber is given in figure 2.

During the tests the pressure gauge was placed by the arcjet thruster therefore the pressure in the arcjet thruster chamber was assumed as equal to the pressure due to the pressure gauge.

The pressure controller guaranteed the supply of the working medium with the pressure of 0.5 atm.

The temperature at the nozzle surface $T_{ns}$ and at the arcjet thruster nozzle exit $T_n$ was determined by the TPP thermocouples with the temperature measurement range of 1573 K.

To perform experimental studies, a control unit with a galvanic decoupler was developed by the push-pull converter diagram and manufactured. The elements in the control unit operate symmetrically (in its cycle half). The converted energy is transmitted twice from the input to the load. Single-phase double half-wave rectification circuit is used in the unit. Transistor keys switching occurs at the frequency of 50 kHz.

The current control is guaranteed by two feedback loops. The first loop provides adjustment and limitation of the input pulse current. The second one stabilizes and regulates the rectified direct current at load. A low resistance diverter is used as a load current sensor. Therefore, the control system is designed by a subordinated regulation principle with inner and outer feedback loops.
Figure 2. Pneumatic-hydraulic schematic for testing arcjet thruster.
1 – arcjet thruster; 2 – pressure gauge; 3 – pressure controller; 4 – evaporator;
5 – electrovalve; 6 – filter; 7 – fuel tank; 8 – nozzle exit thermocouple; 9 – nozzle
surface thermocouple; 10 – arcjet thruster control unit; 11 – laboratory power
supply; 12 – vacuum chamber; 13 – CPS

The control unit operates in power range from 40 to 160 W (upper limit of the power consumption
is determined by the thermal-physical properties of the arcjet thruster constructional materials) and 12-
18 V. To induce main arc discharge in the arcjet thruster, pulses of high voltage up to 5 kV are
formed. Such pulses stop forming at stable operation of main arc discharge and resume at unstable
operation.

Experimental studies were performed in the vacuum chamber having useful capacity of 0.47 m³.
Vacuum pumping system created the pressure of 6 Pa before switching-on and 60 Pa at the arcjet
thruster operation.

Figure 3 shows layout diagram for the performed CPS prototype with the arcjet thruster in the
vacuum chamber before experimenting and the arcjet thruster operation.

Figure 3. Placing CPS with arcjet thruster into a vacuum chamber.
1 – vacuum chamber; 2 – CPS; 3 – arcjet thruster (in operation)
4. Experimental results

During experimental studies of the arcjet thruster, a dark-yellow glow was detected in the vacuum chamber, which can indicate active nitrogen formation. Active nitrogen formation is connected with nitrogen molecules disassociation to free atoms in electric discharge, that occurs at the temperature not less than 3000K [6, 7].

The working medium temperatures at the nozzle exit and surface as well as the pressure in the arcjet thruster chamber has been changing over the entire period of the arcjet thruster operation, that is 10 minutes.

The working medium temperature at the nozzle exit was from 1082 to 1230 K at power consumption from 100 to 160 W. The nozzle surface temperature at the nozzle exit was from 1022 to 1208 K at power consumption from 100 to 160 W. The pressure measured in the arcjet thruster chamber was from 0.55 to 0.6 atm.

At power consumption less than 100 W, the arcjet thruster operated not longer than 10 s. At that moment large power fluctuations and erosion sparks appeared, while there was no ionized gas jet as such.

At the arcjet thruster operation with power consumption from 100 to 140 W, unstable operation modes occurred: power fluctuations and ionized gas jets, erosion sparks were observed (only at the starting time).

At power consumption from 150 to 160 W and at current rate not less than 4 amp, the arcjet thruster operated in a stable way but at the starting time (3-5 s) erosion sparks were present as well.

Visual inspection of the electrodes and the arcjet thruster construction at power consumption from 150 to 160 W exposed no geometrical changes.

Figures 4-7 contain oscillograph charts of unstable arcjet thruster operation.

**Figure 4.** Dependence of current rate on time at unstable operation of the arcjet thruster.

**Figure 5.** Dependence of power consumption on time at unstable operation of the arcjet thruster.

**Figure 6.** Dependence of resistance on time at unstable operation of the arcjet thruster.

**Figure 7.** Dependence of pressure on time at unstable operation of the arcjet thruster.
As a result of the experiments on nitrogen, the temperatures at the nozzle exit $T_c$ and the pressure in the arcjet thruster chamber $p_e$ were measured. The obtained values were used to calculate the arcjet thruster parameters through the mathematical model (1-9) (table 1).

Table 1. Experimental results and design performances of the arcjet thruster.

| Working medium | Measured values | Design values |
|----------------|-----------------|---------------|
|                | $p_e$, kg/cm$^2$ | $T_a$, K | $T_{in}$, K | $N_{AT}$, W | $p_e$, kg/cm$^2$ | $T_c$, K | $P_{sp}$, s | $P_{AT}$, mN | $m$, mg/s |
| Nitrogen       | 0.55            | 1082     | 1022       | 100          | 0.008          | 2961    | 234        | 35.3          | 15.1         |
|                | 0.57            | 1141     | 1137       | 120          | 0.008          | 3123    | 240        | 36.6          | 15.2         |
|                | 0.59            | 1198     | 1191       | 140          | 0.009          | 3279    | 246        | 37.8          | 15.3         |
|                | 0.6             | 1230     | 1208       | 160          | 0.009          | 3366    | 250        | 38.5          | 15.4         |

The obtained experimental data were used to calculate the arcjet thruster characteristics.

The following parameter variations limitations were received: from 2961 to 3366 K for the working medium temperature in the arcjet thruster chamber, from 234 to 250 s for specific impulse, from 35.3 to 38.5 mN for thrust, from 15.1 to 15.4 mg/s for the working medium consumption at power consumption from 100 to 160 W.

5. Results and discussion

Design values for the temperatures in the arcjet thruster chamber were not less than 2961 K. According to [6, 7] active nitrogen formation noticed in the experiments is connected with nitrogen molecules dissociation to free atoms in electric discharge and it occurs at the temperature not less than 3000 K. Therefore, the temperature in the arcjet thruster chamber is confirmed indirectly.

As a result of the studies, lower power consumption limit has been determined (150 W and current rate not less than 4 amp) allowing arcjet thruster to function in a stable way after starting operation (3...5 s).

At power consumption less than 100 W, the arcjet thruster does not function at all. At power consumption from 100 to 140 W, unstable operation modes occur.

Almost equal temperatures at the nozzle exit and surface during the arcjet thruster's steady state operation demonstrate the reliability of the on-going physical processes connected with the heated working medium flow from the nozzle and heat exchange with the arcjet thruster construction.

The observed stability of the electrodes' geometrical parameters and the arcjet thruster construction at power consumption 150...160 W ensures necessary lifetime characteristics for the arcjet thruster required for maneuverable SSC in the investigated mass range.

6. Conclusion

The results obtained experimentally with nitrogen acting as a working medium demonstrate that it is technically possible to produce an arcjet thruster with power consumption 150...160 W and specific impulse up to 250 s, thrust up to 38.5 mN and consumption up to 15.4 mg/s.

Minimal value for the arcjet thruster power consumption guaranteeing stable operation is 150 W at current rate not less than 4 amp.

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