Evaluation of the efficiency of a small-sized electrothermal micro-thrusters with autonomous heating elements

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Abstract. The work is aimed at solving urgent tasks – improving the efficiency of electrothermal micro-thrusters (ETMT) for microsatellites weighing up to 50 kg. The purpose of this work is to evaluate the effectiveness of a small-sized ETMT with Autonomous heating element (AHE) with a diameter of 4 mm on the basis of experimental studies. In the course of experimental studies, the ETMT temperature characteristics were determined for electrical power consumption in the range of 3-30 W using "cold" and "hot" switching schemes. The effectiveness of small ETMT with AHE diameter of 4 mm is a significant increase in temperature AHE and, as a result of heating of the working fluid and reducing the time of reaching the stationary mode of operation compared to ETMT with AHE diameter of 6 mm. The results of experimental studies have shown that a small-sized ETMT be successfully used in microsatellites correction propulsion system (CPS) with a power output of 10-30 W.

1. Introduction

For microsatellites weighing up to 50 kg in the composition of the CPS, electric heating ETMT of various designs are widely used [1–5]. The analysis of ETMT allows us to distinguish among them ammonia ETMT with a tubular heating element (THE) and ETMT with AHE [6, 7].

The main advantage of ETMT with THE is the ability to reserve THE, which dramatically increases the reliability of its operation [6]. At the same time, they have a number of disadvantages, among which we can note: a complex and long-term technology for sealing the output points of current outlets and thermocouples; under reliability conditions, a less energy-efficient "cold" method of starting is used [6].

ETMT with AHE exclude the listed disadvantages of ETMD with THE. ETMT with AHE allows for both "cold" and "hot" launch methods [7]. The "hot" launch method allows increasing the specific thrust impulse of the ETMT with AHE [7].

Further improvement of the ETMT with AHE is associated with a decrease in the overall mass characteristics of the ETMT due to the use of additive technologies in the manufacture of the ETMT case [8]. Studies of an AHE with a diameter of 6 mm (ane metal with two built-in thermocouples), made using additive technologies, confirmed its performance, as well as showed an increase in the AHE temperature and a decrease in the time to enter the stationary mode in comparison with the ETMT, made in the traditional way [8].

Further enhancement of the effectiveness of this type ETMT (high value of specific impulse of thrust, more rapid access to steady state operation and the increase in stationary heating temperatures of the working fluid) is associated with the use of thin-walled AHE diameter of not more than 4 mm and reducing the weight of the hull ETMT through the use of modern additive technology in the manufacture of the body ETMT [8].
2. Problem statement
The task of evaluating the effectiveness of a small-sized ETMT with AHE diameter 4 mm in comparison ETMT with AHE diameter 6 mm, based on experimental studies, is set.

To solve the task at hand:
– 3D model of a small-sized ETMT developed;
– made by Direct Metal Laser Sintering (DMLS) ETMT housing;
– an experimental small-sized ETMT was assembled using a ceramic thin-walled AHE with a diameter of 4 mm;
– experimental studies of a small-sized ETMT with AHE in a vacuum chamber when working on nitrogen in the power consumption range of 3-30 W when using "cold" and "hot" launch methods were carried out;
– the results of experimental studies are analyzed;
– the evaluation of the effectiveness of ETMT in comparison ETMT with AHE with a diameter of 6 mm was carried out.

3. Theory
The use of additive technologies in the manufacture of ETMT has reduced the number of parts in the body from five to one, due to the possibility of manufacturing complex structures with internal cavities and gas ducts (figure 1) [8].

Due to the use of additive technologies in the creation of ETMT, it was possible to reduce the weight of the ETMT body by 12% compared to the ETMT body made in the traditional way (turning, milling, welding) [8]. This was achieved by reducing the number of body parts, reducing the wall thickness of gas lines, and excluding flange connections from the structure. Reducing the weight of the ETMT case leads to a decrease in the heat capacity of the case, and, consequently, to an increase in the heating temperature of the working fluid [8].

Further improvement of the ETMT design is associated with the use of a thin-walled ceramic AHE with a diameter of 4 mm, which provides faster heating of the structure with low energy consumption.

On the basis of the AHE with a diameter of 4 mm, the design of the body of a small-sized ETMT was developed for production by the DMLS method. The 3D model of the ETMT is constructed in such a way that the nozzle of the working fluid supply, the external housing, the internal housing with gas lines, the gas flow generator, the nozzle, and the micro-motor mounting Assembly are formed in one housing (figure 2).
1, 2, 3 – first, second and third gas pipeline circuits

**Figure 2.** 3D model of a small-sized ETMT case

To get rid of unwanted supports, smooth transitions are introduced in the 3D model of small-sized ammonia ETMT. Also, at the junction of the walls and internal elements, instead of sharp edges, fillets are used. The developed design of the ETMT eliminates the need for flanged connections, and also allows you to reduce the thickness of the body walls to 0.5 mm. All these measures allow you to reduce the size and weight of the ETMT.

Heating of the working fluid is carried out in the gas pipeline, which is a screw channel. In the cross-section of the channel, the gas duct has a rectangular shape with dimensions of 2.5x1.0 mm. The cross-section Dimensions of the gas ducts were chosen so that the diameter of the critical section of the nozzle was the smallest size along the entire path of gas movement in the ETMT. The gas pipeline can be divided into three sections: 1 section – from the inlet fitting of the working fluid to the gas pipeline to the annular cavity in the nozzle area; 2 section – from the annular cavity to the ETMT flange; 3 section – part of the gas pipeline formed by the ETMT body and the AHE body (figure 2). For maximum heating of the working fluid, the characteristic dimensions of the gas duct were determined (table 1).

| Circuits of the gas passage | Number of coils | Pitch of turns, \( h \), MM | Section dimensions, \( a \times b \), MM | Equivalent diameter, \( d \), MM | Channel length, \( l \), MM |
|----------------------------|----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1 circuits                 | 4.5            | 6.0                         | 2.5x1.0                     | 1.43                        | 102.6                       |
| 2 circuits                 | 4.0            | 6.0                         | 2.5x1.0                     | 1.43                        | 91.1                        |
| 3 circuits                 | 8.0            | 3.0                         | 2.5x1.0                     | 1.43                        | 127.9                       |

5 ETMT cases were manufactured, their analysis showed the stability of geometric shapes, including the nozzle. Minor roughness of the nozzle shapes was removed mechanically (figure 3).
1 – nozzle; 2 – swirler; 3 – internal flue; 4 – fitting the flow of the working fluid; 5 – ETMT flange; 6 – AHE diameter of 4 mm; 7 – ETMT building

**Figure 3.** Small-sized ETMT with AHE diameter of 4 mm

Housing ETMT was checked for leaks, deviations were found for tightness.

A ceramic thin-walled cylindrical electric heater with a built-in thermocouple with the following characteristics is used as an AHE: rated power – 45 W; operating voltage – 24 V; diameter – 4 mm; length – 65 mm; weight – 2 g.

To reduce the heat loss of the ETMT case, a multi-layer thermal protection was used, similar to the experimental studies of ETMT with a 6 mm diameter AHE [8].

Experimental studies of a small-sized ETMT were carried out as part of a prototype CPS in a vacuum chamber using nitrogen as a working fluid (figure 4). The temperature parameters thermocouple were transmitted to the computer by means of a multichannel temperature meter.

1 – CPS prototype; 2 – vacuum chamber; 3 – automation elements; 4-ETMT; 5 – fitting the flow of the working fluid

**Figure 4.** Installing the CPS in the vacuum chamber

### 4. Experimental results

Experimental studies of ETMT with AHE with a diameter of 4 mm were carried out using "cold" and "hot" switching schemes in the power range of 3–30 W with a temperature limit of AHE 1073 K.

The results of experimental studies of small-sized ETMT are presented in figures 5–9 and in tables 2, 3.
Figure 5. Dependence of the ETMT temperature on the operating time for different power input according to the "cold" switching scheme

Table 2. Results of experimental studies of a small-sized ETMT using a "cold" launch scheme

| Power, served on AHE ETMT, W | The voltage at AHE, V |
|-----------------------------|---------------------|
| 3 W                         | 6.84                |
| 4 W                         | 7.90                |
| 5 W                         | 8.83                |
| 10 W                        | 12.49               |
| 15 W                        | 15.30               |
| 20 W                        | 17.66               |
| 25 W                        | 19.75               |
| 30 W                        | 21.63               |

| Time, sec | Temperature ETMT, K |
|-----------|---------------------|
| 0         | 298.4 298.7 297.6 295.8 297.7 298.7 297.3 296.2 |
| 100       | 438.0 475.7 513.5 672.6 831.8 958.3 1043.0 -    |
| 200       | 460.0 502.6 545.2 719.6 894.1 1025.5 - -        |
| 300       | 473.0 518.2 563.5 742.7 921.9 - - -             |
| 400       | 481.8 529.2 576.2 760.0 943.8 - - -             |
| 500       | 488.1 536.4 584.8 770.8 956.9 - - -             |
| 600       | 492.8 541.8 590.7 777.0 963.4 - - -             |
| 700       | 496.3 546.2 595.8 781.3 966.8 - - -             |
| 800       | 499.6 549.6 599.6 784.2 968.9 - - -             |
| 900       | 501.8 552.0 602.2 786.2 970.11 - - -            |
| 1000      | 503.5 554.1 604.8 788.1 971.5 - - -             |
| 1100      | 504.62 555.4 606.2 789.5 972.7 - - -             |
| 1200      | 505.5 556.9 608.2 791.2 974.2 - - -             |

Figure 6. Dependence of the temperature ETMT on the operating time at different temperatures supplied power according to the "hot" switching scheme
Table 3. Results of experimental studies of a small-sized ETM using a "hot" launch scheme

| Power, served on AHE ETMT, W | 3   | 4   | 5   | 10  | 15  | 20  | 25  | 30  |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| The voltage at AHE, V       | 6.84| 7.90| 8.83| 12.49| 15.30| 17.66| 19.75| 21.63|
| Time, sec                   | 0   | 100 | 200 | 300 | 400 | 500 | 600 | 700 |
| Temperature ETMT, K         | 298.9| 298.3| 297.6| 300.7| 302.4 | 295.2| 294.1 | 297.5 |

Figure 7. Typical ETMT operation sequence diagram when the "cold" process start (for 10 W of power consumption example)

Figure 8. Typical ETMT operation sequence diagram when the "hot" start process (10 watts power consumption example)
"Cold" start process

$1 - 5 \text{ W}; \ 2 - 10 \text{ W}; \ 3 - 15 \text{ W}$

$t_1, t_2, t_3$ – time to ETMT at quasi-stationary mode of operation

Figure 9. Dynamic heating ETMT at different applied power

Analysis of the results shown in the graphs (figures 5–9) and in tables 2, 3 showed:

– the dynamics of the output of a small-sized ETMT to the operating mode significantly depends on the power consumption of the ETMT and the method of launch being implemented;

– for "cold" process start time output ETMT quasi-stationary mode when varying the power supplied to ane ETMT it was: $3 \text{ W} - 300 \text{ sec}; \ 4 \text{ W} - 350 \text{ sec}; \ 5 \text{ W} - 400 \text{ sec}; \ 10 \text{ W} - 500 \text{ sec}; \ 15 \text{ W} - 600 \text{ sec};$ for $20-30 \text{ W}$ achieved limit temperature $1073 \text{ K}$ in less than $300 \text{ sec}$;

– for "hot" process start time output ETMT quasi-stationary mode when varying the power supplied to ane ETMT was: $3 \text{ W} - 100 \text{ sec}; \ 4 \text{ W} - 150 \text{ sec}; \ 5 \text{ W} - 280 \text{ sec}; \ 10 \text{ W} - 380 \text{ sec}; \ 15 \text{ W} - 480 \text{ sec}; \ 20 \text{ W} - 500 \text{ sec};$ at $25-30 \text{ W}$ of power limit temperature reached $1073 \text{ K}$ during from $\approx 100 \text{ sec}$;

– during "cold" process start temperature and restriction ETMT $1073\text{ K}$ ETMT following maximum temperature attained: $3 \text{ W} - 505.2 \text{ K}; \ 4 \text{ W} - 556.9 \text{ K}; \ 5 \text{ W} - 608.2 \text{ K}; \ 10 \text{ W} - 791.2 \text{ K}; \ 15 \text{ W} - 961.0 \text{ K}; \ 20-30 \text{ W} - 1073\text{ K}$;

– when the "hot" process start temperature and restriction ETMT $1073\text{ K}$ ETMT following maximum temperature attained: $3 \text{ W} - 505.5 \text{ K}; \ 4 \text{ W} - 558.6 \text{ K}; \ 5 \text{ W} - 628.4 \text{ K}; \ 10 \text{ W} - 818.7 \text{ K}; \ 15 \text{ W} - 974.2 \text{ K}; \ 20 \text{ W} - 1076.9 \text{ K}; \ 25-30 \text{ W} - 1073 \text{ K}$.

A comparative analysis with a compact ETMT AHE diameter of $4 \text{ mm}$ with the same ETMT AHE diameter of $6 \text{ mm}$ showed a decrease in body weight by $30\%$, while all mass ETMT $35\%$. Due to the weight reduction Reduction design heat capacity ETMT led to increased peak temperatures ETMT with AHE diameter of $4 \text{ mm}$ compared with ETMT with AHE diameter $6 \text{ mm}$, manufactured by additive technology and ETMT with AHE diameter of $6 \text{ mm}$, generated on the conventional technology (milling, turning, welding). Comparison ETMT characteristics shown in table 4 and figure 10 [8, 9].
1 – ETMT AHE diameter of 4 mm; 2 – ETMT AHE diameter of 6 mm

*Figure 10.* Comparison ETMT temperature characteristics at different applied power

| ETMT AHE diameter of 6 mm, made in the traditional way | ETMT AHE diameter of 6 mm, produced by additive technology | ETMT AHE diameter of 4 mm, produced by additive technology |
|--------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Housing diameter ETMT, mm                             | 12                                                       | 10                                                       |
| Housing length ETMT, mm                               | 70                                                       | 70                                                       |
| Housing weight ETMT, g                                 | 25                                                       | 22                                                       |
| Weight ETMT, g                                        | 55                                                       | 52                                                       |
| Temperature (K) and the output time (sec) on a quasi-stationary regime ETMT at 5 W | 391.5; 400                                               | 400.4; 400                                               |
| Temperature (K) and the output time (sec) on a quasi-stationary regime ETMT at 10 W | 479.9; 500                                               | 495.6; 500                                               |
| Temperature (K) and the output time (sec) on a quasi-stationary regime ETMT at 15 W | 622.8; 600                                               | 631.5; 600                                               |
| Temperature (K) and the output time (sec) on a quasi-stationary regime ETMT at 20 W | 663.8; 600                                               | 675.4; 600                                               |
| Temperature (K) and the output time (sec) on a quasi-stationary regime ETMT at 25 W | 740.6; 700                                               | 758.4; 700                                               |
| Temperature (K) and the output time (sec) on a quasi-stationary regime ETMT at 30 W | 790.4; 600 c                                            | 817.3; 600 c                                            |
| Temperature (K) and the output time (sec) for a limited fixed mode ETMT at 20 W | –                                                       | 1073; 295                                               |
| Temperature (K) and the output time (sec) for a limited fixed mode ETMT at 25 W | –                                                       | 1073; 115                                               |
| Temperature (K) and the output time (sec) for a limited fixed mode ETMT at 30 W | –                                                       | 1073; 83                                                |
5. Conclusion

1. Experimental tests have shown that the use of a small-sized ETMT AHE diameter of 4 mm compared with ETMT with AHE 6 mm in diameter provides the following effects:
   - weight reduction of 30 g;
   - increase in temperature at the stationary ETMT "cold" start method:
     - for 5 W on ≈203 K;
     - for 10 W on ≈295 K;
     - for 15 W on ≈401.8 K;
     - to 20 W achieved a limited fixed mode 1073 K for 295 sec;
     - to 25 W achieved a limited fixed mode 1073 K for 115 sec;
     - to 25 W achieved a limited fixed mode 1073 K for 83 sec.
2. The use of a "hot" circuit run ETMT reduces the output time ETMT a stationary mode to a ≈120 sec, wherein quasi-stationary temperature regime is not reduced in comparison with a "cold" start circuit.
3. Small ETMT AHE with a diameter of 4 mm can be used in the CPS to the microsatellite with the restriction allocated power to 30 W.

References
[1] Cifali G, Gregucci S, Andreussi T and Andrenucci M 2017 Proc. 35th Int. Electric Propulsion Conf. (Atlanta: Georgia Institute of Technology) IEPC-2017-371
[2] Romei F, Grubišić A, Lasagna D and Gibbon D 2017 7th European Conference for Aeronautics and Space Sciences (EUCASS) DOI: 10.13009/EUCASS2017-378.
[3] Coxhill I, Gibbon D and Drube M 2008 Proc. 5th Int. Spacecraft Propulsion Conf. (Heraklion) pp 1–9
[4] Wright D and Kulacki G 2008 Union of Concerned Scientists.
[5] Sweetin M N, Lawrence T and Leduc J 1999 Proceedings Institution of Mechanical Engineers v. 213, part GP, pp 223 – 231
[6] Blinov V N, Shalay V V, Kositsin V V, Vavilov I S, Lukyanchik A I and Ruban V I 2016 Indian J Sci Technol 9(19) DOI: 10.17485/ijst/2016/v9i19/93893.
[7] Blinov V N, Shalay V V, Kositsin V V, Vavilov I S, Lukyanchik A I and Ruban V I 2016 Indian J Sci Technol 9(19) DOI: 10.17485/ijst/2016/v9i19/93912.
[8] Blinov V N, Shalay V V, Kuznetsov V I, Yakovlev A B, Yachmenev P S, Luyanchik A I and Kositsin V V 2018 IOP Conf. Series: Journal of Physics: Conf. Series 1050 (2018) 012013 DOI :10.1088/1742-6596/1050/1/012013.
[9] Blinov V N, Vavilov I S, Kositsin V V, Luyanchik A I, Ruban V I and Shalay V V 2018 IOP Conf. Series: Journal of Physics: Conf. Series 944 (2018) 012020 DOI: 10.1088/1742-6596/944/1/012020.