Indian Journal of Science and Technology, Vol 9(19), DOI: 10.17485/ijst/2016/v9i19/93893, May 2016
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

# Design Features and Studies of Ammonia Electrothermal Microthrusters with Tubular Heating Elements for Small Space Vehicles

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## Abstract

**Background/Objectives:** The article studies the definition of structural appearance of Electro Thermal Micro Thrusters (ETMT) with Tubular Heating Elements (THE) for Correcting Propulsion Systems (CPS) of maneuverable Small Space Vehicles (SSV). **Methods:** On the basis of an integrated approach we have defined structural appearance of ETMT with THE, conforming to the requirements to ensure minimum weight, manufacturability and maintainability. **Findings:** Structural diagrams of ETMT with THE having various lengths have been developed that provide increase in specific burst of power of ETMT in conditions of limited power consumption. Ammonia-operated prototypes of ETMT with THE have been manufactured and tested in a vacuum chamber under conditions most closely resembling the operational ones. The conducted experimental studies have shown the possibility of using ETMT with THE as part of CPS SSV in ETMT power consumption range varying from 60 to 70 W. **Application/Improvements:** These experimental studies are a continuation of works in creating ETMT of various designs and are of practical interest when developing CPS for maneuvering SSV[7].

**Keywords:** Correcting Ammonium Propulsion System, Electrothermal Microthruster, Maneuverable Small Space Vehicle, Specific Burst of Power, Tubular Heating Element

## 1. Introduction

The modern stage of outer space exploration is characterized by the large-scale development and use of SSV weighing 10-400 kg launched by group and hosted ways using launch vehicles for solving scientific and application problems[1–4].

In the course of SSV functioning, the orbital maneuvering objectives include error correction of SSV orbital injection by launch vehicles, control of orbital parameters, interorbital maneuvering, construction of SSV orbit groups, injection of SSV into orbit of utilization, etc. To solve the arising problems of SSV orbital maneuvering, CPSs with electrothermal microthrusters of different design, including ammonia ETMT, are incorporated into SSVs.[1–13]

The designed ammonium ETMT with THE having thrust of 30mN are characterized by the power-to-thrust ratio up to 2 W/mN and used as part of SSVs with a weight of 30 to 400 kg[7,11,12,15].

The main advantage of ETMT with THE is an opportunity to back up THE. In terms of design ETMT is manufactured with the main and the back up THE and with two thermocouples, which enhances sharply its operational reliability[7,11,12].

It is worthwhile to note the following shortcomings of the existing designs of ETMT with THE[7,11,12]:

- terminal and propellant-feed pipe protection housings in the form of machined and milled parts have considerable weight, which increases gross warmed up mass

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of ETMT and reduces specific burst of power of the microthruster;

- gas flow swirlers in the form of inclined gas inlet slots have low efficiency of the gas flow swirl, which reduces heating degree of the working fluid and, consequently, specific burst of power of the microthruster;
- complex, lengthy and piece-by-piece sealing of terminal, thermocouple and propellant-feed pipe exit points with a special sealant taking up to ten days and more with regard to possible repair works;
- *in case of unsuccessful sealing of the microthruster, and thermocouple failure when testing the assembled ETMT the procedure of tightness recovery and thermocouple replacement is connected with a full reassembling of ETMT with damaged second thermocouple, heating elements, parts of ceramic tubes.*

Improved ETMT with THE having minimum weight is an alternative eliminating the above shortcomings, wherein[13]:

- terminal body is made as a flat bracket;
- free access to the sealing points of ETMT is provided;
- thermocouples are installed with the possibility of their dismantling and minimum reassembling of ETMT.

The basis of the adopted methodology of the improved ETMT with THE having minimum weight is formed by the experimental development of new technical solutions in conditions most closely resembling the operational ones: tests in a vacuum chamber using ammonia as part of CPS development prototype with a control unit.

In this regard, experimental studies of the improved ETMT with THE in the power range of 60-70 W are of practical interest to create CPS for maneuvering SSV.

## 2. Literature Review

The article deals with electrothermal ETMTs in which operating particles are accelerated due to thermal effects of electric currents, whereas the direction of the velocity vector is determined by the geometry of the microthruster nozzle. Electrothermal ETMT are widely used for SSV as part of CPS[1–4,7–10].

An increased focus should be put on electrothermal ETMTs manufactured by Surrey Satellite Technology Limited (SSTL).

SSTL developed various ETMTs: that of "Mark" series; butane-fueled with a thrust of 50 mN and energy consumption up to 50 W; xenon- and nitrogen-fueled with a thrust of 20-50 mN and energy consumption up to 50 W, and a steam one[1–4,8] (Figure 1).

Prior art ETMTs have terminals for electric energy supply with considerable structure weight, which increases the warmed-up mass of ETMT. Thus, ETMT, shown in Figure 2, is 100 mm long and weighs 100 g at a thrust of 20-50 mN[8].

Wire heating elements, for example, made of nichrome wire[14], are often used as heaters for electrothermal ETMTs (Figure 3).

To provide electrical insulation wire heaters are laid into the two-channel ceramic tubes and in this case the heater itself refers to THE[7,11,12] (Figure 4).

THE have been used for ammonia ETMT, as part of CPS and SSV providing achievement of high values characteristic speeds with a minimum structure weight and fuel consumption.[6,7,11,12,15]

Ammonia ETMTs with THE are manufactured with conical and bell nozzles and made primarily T-shaped to decrease dimensions along the longitudinal axis[6,7,11,12,15] (Figure 5).

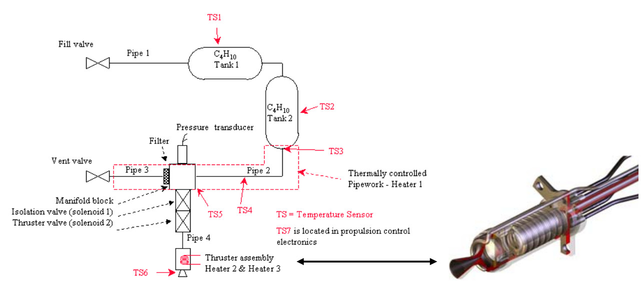
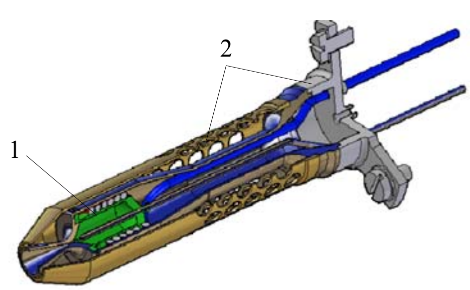
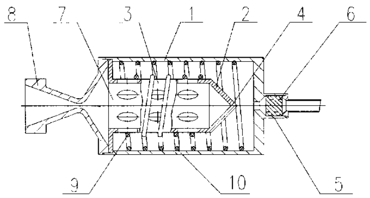



**Figure 1.** ETMTs manufactured by SSTL as part of CPS



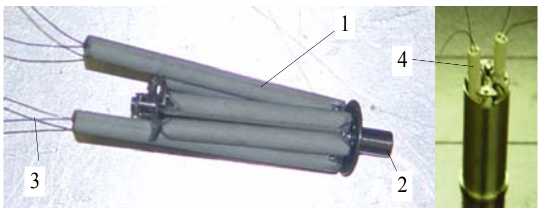

1 – ETMT; 2 – terminal casing

**Figure 2.** Xenon- fueled ETMT manufactured by SSTL



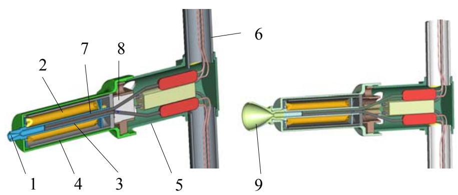

1 – fuel thermal decomposition chamber; 2 – hollow liner; 3 – perforated wall; 4 – bottom; 5 – injector; 6 – swirler; 7 – liner open end; 8 – nozzle; 9 – heater; 10 – additional heater.

**Figure 3.** ETMT with wire heater




1 – two-channel ceramic tube; 2 – gas duct with nozzle; 3 – nichrome wire; 4 – THE as part of ETMT casing

**Figure 4.** THE general layout

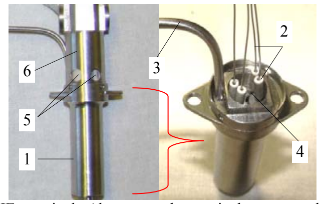



1 – conical nozzle made integral with the gas duct; 2 – THE; 3 – gas duct; 4 – casing (outer and inner); 5 – main terminal casing; 6 – casing for additional terminals; 7 – thermocouple; 8 – ETMT sealing point; 9 – detachable bell nozzle.

**Figure 5.** ETMT with cylindrical terminal casings

These ammonia ETMTs have thrust of 30 mN and energy consumption of 60 W, their total length making 78 mm, main terminal casing is 35 mm long and 16 mm in diameter, casing for additional terminals are 2×25 mm long and 10 mm in diameter, ETMT weight is 80 g.

The protective terminal casings and fuel feed line made in the form of turned and milled parts contribute to the increase in ETMT structure weight, which increases the overall warmed-up mass of ETMT and reduces the specific burst of power of the microthruster. It also leads to a complex, gradual and prolonged technology for sealing exit points of terminals, thermocouples, and fuel feed line with a special sealant. The thermocouple replacement procedure in case of its failure is associated with a full reassembly of ETMT, damaging the second thermocouple, heating elements and a part of the ceramic tubes[7,11,12] (Figure 6).




1 – ETMT; 2 – THE terminals (thermocouple terminals are not shown); 3 – ammonia feeding line; 4 – sealing cavity; 5 – sealing holes; 6 – main terminal casing.

**Figure 6.** Design of ETMT sealing point

## 3. Research Methods and Materials

To conduct experimental testing the following units were manufactured:

- ETMT with THE having cylindrical terminal casing and gas duct 29 mm long (Figure 7);
- two ETMTs with THE having flat terminal casing and different gas duct length: 29 mm and 16 mm (Figures 8-10).

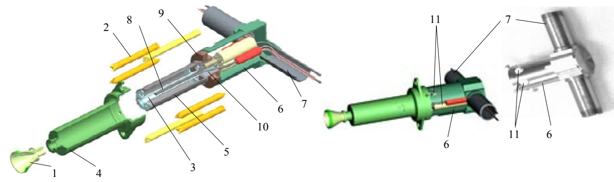
Design features of the improved ETMT with THE include:

- flat terminal casing;
- thermocouple installed at the nozzle side;
- swirler made in the form of spring;
- free access to ETMT sealing points;
- ammonia side-feed via chamber.

The created ETMTs with THE possess enhanced specific burst of power and improved technological properties due to:

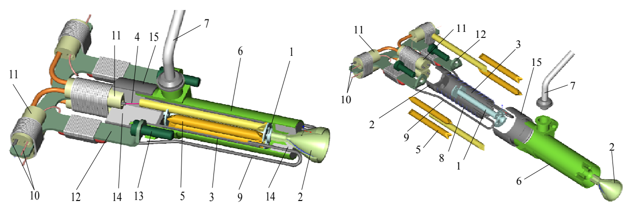
- ammonia temperature increase by decreasing the structure weight;
- ensured ammonia swirl when moving inside the microthruster through the spring swirler;
- simplified assembly procedure;
- improved sealing quality by providing access to the microthruster sealing points;
- provided recoverability with heating elements and casing parts kept untouched in the course of the microthruster reassembly in case of thermocouple failure.

ETMTs with cylindrical terminals (Figure 7) differ in weight from those with flat terminals (Figure 8) primarily due to various designs of the microthruster current-carrying parts.



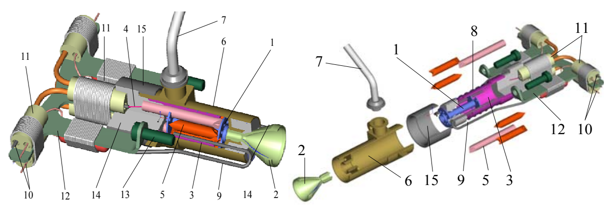
1 – detachable bell nozzle joinable with gas duct; 2 – THE; 3 – gas duct; 4 –outer casing; 5 – inner casing; 6,7 – main and additional terminal casings; 8 – thermocouple; 9 – nut; 10 –ETMT sealing zone; 11 – sealing holes.

**Figure 7.** ETMT with cylindrical terminal casing



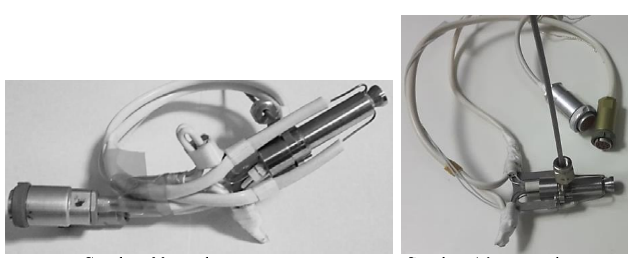
1 – gas duct; 2 – detachable nozzle; 3 – liner; 4 – heating elements; 5, 11 – two-channel ceramic tubes; 6 - chamber; 7 – ammonia feeding line; 8 – spring swirler; 9 – thermocouple; 10 – terminals; 12 – terminal casing; 13 – screws; 14 – sealant; 15 – extension.

**Figure 8.** ETMT with flat terminal casings having gas duct length of 29 mm



1 – gas duct; 2 – detachable nozzle; 3 – liner; 4 – heating elements; 5, 11 – two-channel ceramic tubes; 6 – chamber; 7 – ammonia feeding line; 8 – spring swirler; 9 – thermocouple; 10 – terminals; 12 – terminal casing; 13 – screws; 14 – sealant; 15 – extension.

**Figure 9.** ETMT with flat terminal casings having gas duct length of 16 mm



Gas duct 29 mm long    Gas duct 16 мм mm long

**Figure 10.** Experimental prototypes of ETMT with THE

For ETMT with cylindrical terminal design the structure area makes 3530 mm$^2$, while for ETMT with flat terminal design it is 1100 mm$^2$. Terminal structure thickness being similarly equivalent, terminal weight will be reduced by 69 %, and ETMT weight - by 18 %.

ETMT weight reduction will result in the increase in ETMT heating temperature.

The microthruster is sealed by applying a special sealant. The sealed cavities are open for sealant application and consolidation in the course of drying. This provides a solid structure of the sealant and, consequently, a high degree of the microthruster sealing.

If the microthruster thermocouple as the ‘weakest’ element failed in the process of testing it is replaced by removing the sealant, and all structural elements of the microthruster remain untouched.

Ammonia is side-fed into ETMT via the chamber, which simplifies sealing of ETMT end cavity with outgoing terminals (Figure 11).
ETMTs with cylinder and flat terminals are (Figure 11):

- in ETMT with cylinder terminal casing temperature is measured in the gas duct cavity;
- in ETMT with flat terminal casing temperature is measured in THE placement cavity.

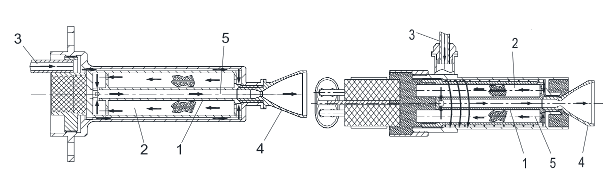
In the first case thermocouple readings will be higher, which should be considered when analyzing temperature state of ETMT with different form of terminal casings during tests.

In addition, when installing the main and backup THEs and thermocouples and controlling ETMT temperature, it is required to take the thermocouple located nearby the operating THE as a master one.

ETMT consumed energy control option is also possible, in that case thermocouples are used only to get the temperature information.

The following parameters were employed during the experimental tests:

- ‘cold’ starting method when ammonia was fed into ETMT simultaneously with applying voltage to THE;



a    b

1 – gas duct; 2 – THE; 3 – ammonia inlet; 4 – nozzle; 5 – zone for temperature measuring with thermocouple

**Figure 11.** Scheme of ammonia flow and temperature measuring zone in ETMT with cylindrical **(a)** and flat **(b)** terminal casing

- For ETMT with THE with cylindrical terminal casing: 60 W energy consumption, preset maintained temperature 873 K, 973 K, 0.4 W/s energy gain rate;
- For ETMT with THE having flat terminal casing and gas duct length of 29 mm:
    - a) 60 W energy consumption, 987 K temperature shutdown level, 0.4 W/s energy gain rate;
    - b) 70 W energy consumption, 1133 K temperature shutdown level, 0.7 W/s energy gain rate;
- For ETMT with THE having flat terminal casing and gas duct length of 16 mm:
    - a) 60 W energy consumption, preset maintained temperature of 973 K, 0.4 W/s energy gain rate;
    - b) 70 W energy consumption, 1015 K temperature shutdown level, 0.4 W/s energy gain rate.

Experimental tests were carried out on ammonia-fueled ETMT in a vacuum chamber using the CPS development prototype (Figure12).

## 4. Results of the Experimental Tests Performed on Electrothermal Microthrusters with Tubular Heating Elements

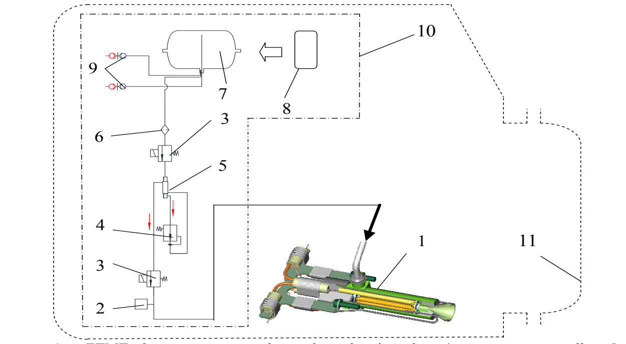
Results of the experimental tests performed on ETMT with THE at 'cold' starting are shown in the temperature curves, where: 1 – temperature in ETMT, recorded by the thermocouple; 2 – THE energy consumption, W; 3 – heater current ×100; 4 – ammonia feed detector: 0 – "No", 100 – "Yes" (Figures 13-18).

Based on the obtained dependencies comparative temperature curves have been plotted for ETMT with THE at energy consumption of 60 and 70 W having different energy gain rate: 0.4 W/s, 0.7 W/s (Figures 19, 20).

## 5. Discussion

The conducted experimental research has shown:

1. For ETMT with THE having cylindrical terminal casing, 60 W energy consumption, 0.4 W/s energy gain rate:
    - it takes ≈195 s to reach 873 K preset temperature control mode (Figure 13);
    - it takes ≈230 s to reach 973 K preset temperature control mode (Figure 14).




1 – ETMT; 2 – pressure transducer; 3 – electric valve; 4 – pressure controller; 5 – evaporator; 6 – filter; 7 – propellant tank; 8 – CPS control unit; 9 – fill and drain couplings; 10 – test stand; 11 – vacuum chamber

**Figure 12.** Scheme for testing ammonia-fueled ETMT with THE in a vacuum chamber

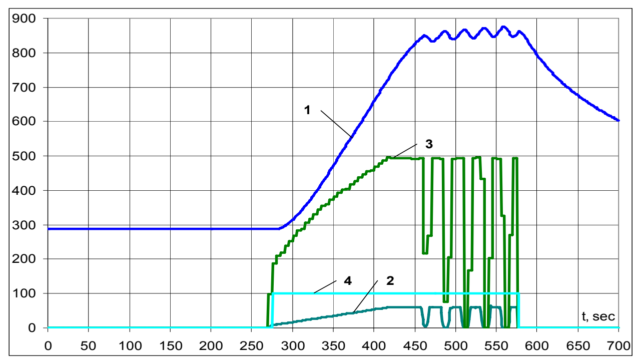



**Figure 13.** Time changes in the electrical parameters and pressure transducer ETMT with THE: terminal casing cylindrical; 60 W energy consumption; 0.4 W/s energy gain rate; 873 K temperature limitation

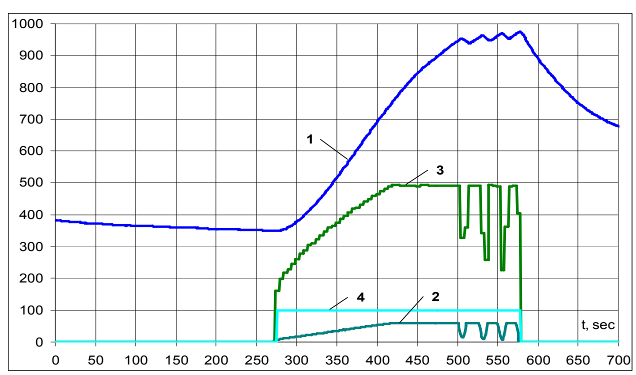



**Figure 14.** Time changes in the electrical parameters and temperatures for ETMT with THE: cylindrical terminal casing; 60 W energy consumption; 0.4 W/s energy gain rate; 973 K temperature limitation

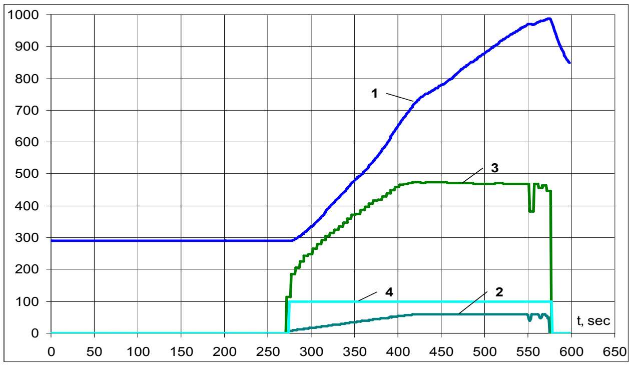



**Figure 15.** Time changes in the electrical parameters and temperatures for ETMT with THE: flat terminal casing; gas duct length of 29 mm; 60 W energy consumption; energy gain rate of 0.4 W/s; 987 K temperature shutdown level

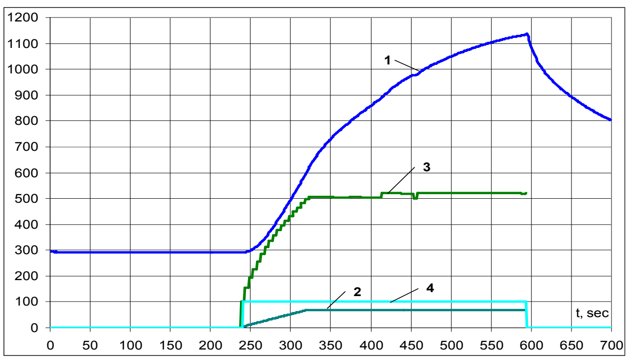



**Figure 16.** Time changes in the electrical parameters and temperatures for ETMT with THE: flat terminal casing; gas duct length of 29 mm; 70 W energy consumption; energy gain rate 0.7 W/s; 1133 K temperature shutdown level

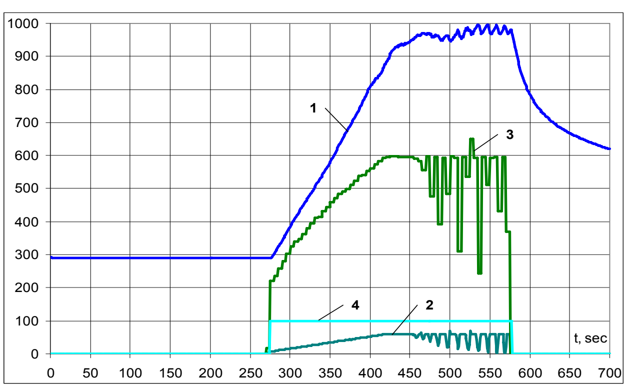



**Figure 17.** Time changes in the electrical parameters and temperatures for ETMT with THE: flat terminal casing; gas duct length of 16 mm; 60 W energy consumption; energy gain rate 0.4 W/s; 973 K temperature limitation

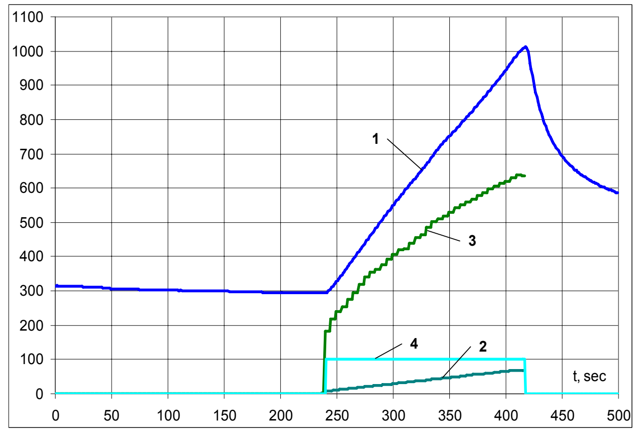
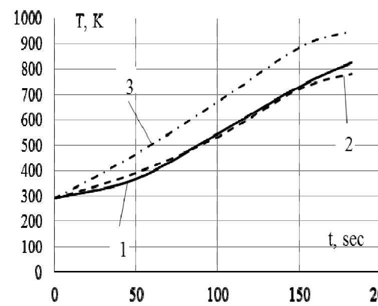
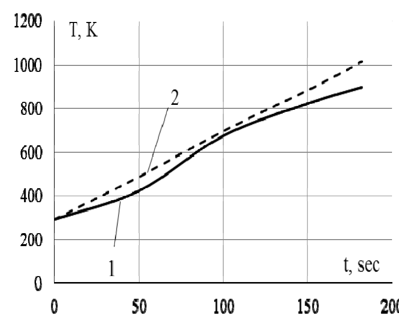



**Figure 18.** Time changes in the electrical parameters and temperatures for ETMT with THE: flat terminal casing; gas duct length of 16 mm; 70 W energy consumption; energy gain rate 0.4 W/s; 1013 K temperature shutdown level




1 – ETMT with cylindrical terminal casings having gas duct length of 29 mm (Figure 12); 2 – ETMT with flat terminal casings having gas duct length of 29 mm (Figure 14); 3 – ETMT with flat terminal casings having gas duct length of 16 mm (Figure 16).

**Figure 19.** Time changes in the temperatures for ETMT with THE at 60 W energy consumption and 0.4 W/s energy gain rate




1 - ETMT with flat terminal casings having gas duct length of 29 mm, energy gain rate 0.7 W/s (Figure 15); 2 - ETMT with flat terminal casings having gas duct length of 16 mm, energy gain rate 0.4 W/s (Figure 17)

**Figure 20.** Time changes in the temperatures for ETMT with THE with 70 W energy consumption and different energy gain rate

2. For ETMT with THE having flat terminal casing and gas duct length of 29 mm:
    - 973 K temperature rise time amounted to ≈275 s at 60 W energy consumption and 0.4 W/s energy gain rate (Figure 15);
    - 1140 K temperature rise time amounted to ≈360 s at 70 W energy consumption and 0.7 W/s energy gain rate (Figure 16).
3. For ETMT with THE having flat terminal casing and gas duct length of 16 mm:
    - 973 K temperature rise time amounted to ≈180 s at 60 W energy consumption and 0.4 W/s energy gain rate (Figure 17);
    - 1013 K temperature rise time amounted to ≈182 s at 70 W energy consumption and 0.4 W/s energy gain rate (Figure 18).
4. For ETMT with THE having cylindrical terminal casing temperature change up to 847 K can be described by equation (value of approximation validity $R^2$= 0.98, t – time): T=3.02t+257.
5. For ETMT with THE having cylindrical terminal casing temperature change up to 945 K can be described by equation ($R^2$= 0.99): T=2.75t+323.
6. For ETMT with THE having flat terminal casing and gas duct length of 29 mm temperature change up to 958 K can be described by equation ($R^2$= 0.98): T=2.55t+290.
7. For ETMT with THE having flat terminal casing and gas duct length of 29 mm temperature change up to 1133 K can be described by equation ($R^2$= 0.99): $T=-0.006\, t^2+4.555t+266$.
8. For ETMT with THE having flat terminal casing and gas duct length of 16 mm temperature change up to 947 K can be described by equation ($R^2$= 0.99): T=3.79t +288.
9. For ETMT with THE having flat terminal casing and gas duct length of 16 mm temperature change up to 1033 K can be described by equation ($R^2$= 0.99): T=3.84t +299.
10. Comparative analysis of temperature dependences of ETMT with THE having different terminal casing form, gas duct length, energy consumption, energy gain rate, and also with regard to differing temperatures measured by thermocouples (in the cavity of THE location, in the gas duct cavity) has shown:
    - obtained temperature dependence of ETMT with THE having flat terminal casing is close to temperature dependence of ETMT with THE with cylindrical terminal casing; with regard to differing temperatures measured by thermocouples (in the cavity of THE location - $T_{THE}$, in the gas duct cavity – $T_g$; TTHE < Tg) temperature inside the gas duct of ETMT with THE having flat terminal casing will be higher, which indicates its better heating capacity;
    - temperature characteristics of ETMT with THE having flat terminal casing and gas duct length of 16mm are higher by ≈ 137-169 K than temperature characteristics of ETMT with gas duct 29 mm long;
    - energy gain rate during ETMT operation considerably influences ETMT temperature characteristics;
    - temperature characteristics of ETMT having flat terminal casing, gas duct length of 16 mm and energy gain rate of 0.4 W/s exceed temperature characteristics of ETMT with gas duct 29 mm long and high energy gain rate of 0.7 W/s only by 20-112 K.
11. Manufacturing and assembly of experimental prototypes of ETMT with THE having flat terminal casings have shown (Figure 10):
    - flat parts of terminal casing have no technological constraints and may be manufactured having practically any thickness, which results in reduction of total weight of ETMT and increase in temperature characteristics;
    - time for ETMT cavity sealing reduced from 10 days to 1 day;
    - ETMT cavity sealing quality was improved by means of free access to the pressurized cavities and absence of ammonia feeding line therein;
    - it is possible to replace thermocouples retaining all parts of ETMT.
12. The conducted research confirms the possibility to obtain enhanced specific characteristics of ETMTs with THE having flat terminal casings.

## 6. Conclusion

1. ETMT with THE has been manufactured and experimentally tested as part of CPS in vacuum, having the following properties:

    - rated thrust: 30 mN;
    - gas duct length: 29 mm;

- terminal casing: cylindrical;
- starting method: cold start;
- energy consumption: 60 W;
- fuel type: ammonia;
- energy gain rate: 0.4 W/s;
- temperature limitation: 873 K, 973 K.

2. ETMTs with THE have been manufactured and experimentally tested as part of CPS in vacuum, having the following properties:
    - rated thrust: 30 mN;
    - gas duct length: 29 mm; 16 mm;
    - terminal casing: flat;
    - starting method: cold start
    - energy consumption: 60 W, 70 W;
    - fuel type: ammonia;
    - energy gain rate: 0.4 W/s, 0.7 W/s;
    - maintained temperature limitation: 973 K;
    - ETMT shutdown temperature: 987 K, 1013 K, 1133 K.
3. The obtained results have shown that ETMT with THE having flat terminal casing will ensure:
    - specific impulse increase by 6-8 %;
    - high degree of ETMT sealing, faster production and assembly time, recoverability, design manufacturability, and weight-saving.
4. ETMT with THE having flat terminal casing:
    - may be used as part of CPS for maneuverable SSV within a wide range of different weight characteristics at energy consumption of 60-70 W;
    - are competitive microthrusters among the ammonia ETMT with THE applied in practice.

## 7. Acknowledgement

The paper represents results of works carried out in the context of Grants Agreement No. 14.574.21.0104 as of 08.09.2014 (Unique Identifier of Applied Research RFMEFI57414X0104) concluded with the Ministry of Education and Science of the Russian Federation and related to applied researches.

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