

Design Features and Research of Electrothermal Microthrusters with Autonomous Heating Elements for the Purposes of Small Space Vehicle Orbital Manoeuvring

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Abstract

The paper studies the definition of design-basis appearance of Electrothermal Microthrusters (ETMT) with Autonomous Heating Elements (AHE) for Correcting propulsion System (CPS) of manoeuvrable Small Space Vehicles (SSV). The findings of present study are of particular practical interest in connection with creation of CPS for manoeuvrable SSV of ultra-low mass (under 10 kg). In the framework of the taken approach, multipurpose method of structural design has defined design parameters and design appearance of ETMT. Different characteristics of ETMT are provided due to replaceable conical and bell nozzle linings' usage without change of ETMT basic design. Design maps of ETMT with AHE have been developed, aimed to specific performances' upgrade of CPS in conditions of low power consumption. The results of undertaken land experimental study are quoted, including conditions of vacuum-chamber using nitrogen and air as working medium of CPS. Basing on the undertaken experimental study the possibility in principle of the usage of ETMT with AHE as part of CPS for space vehicles of gross mass under 10 kg is shown. Moreover, design map, implementation approach and further upgrade of ETMT with AHE are defined, among which it is possible to emphasize the design map of ETMT integrated with evaporator, providing the increase of specific burst of power up to 30-35 % within allocated power consumption as part of SSV.

Keywords: Autonomous Heating Element, Correcting Ammonium Propulsion System, Electrothermal Microthruster, Manoeuvrable Small Space Vehicle, Specific Burst of Power

1. Introduction

The present stage of exploration of outer space is characterized by large-scale creation and application of SSV weighing 10-140 kg in order to solve scientific and application problems, initiated by group and hosted methods^{4,10,11}. Consequently relevant objectives of SSV orbital manoeuvring have arisen: Error correction of injection, control of orbital parameters, interorbital manoeuvring, construction of SSV orbit groups, injection of SSV into orbit of utilization etc.

Electrical microthrusters used for orbital manoeuvring are characterized by high cost of thrust (for example, fixed plasma engines under 20 W/mN and more), that does not allow using them for SSV with tight energy supply. Thermocatalytic microthrusters at low cost of thrust have greater thrust (100-500 mN), which is unacceptable for SSV due to inadmissible disturbances during their work.

Designed ammonium Electrothermal Microthrusters (ETMT) with Tubular Heating Elements (THE) with thrust of 30mN are characterized by the cost of thrust up

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to 2 W/mN and are made good use of as part of a range of SSV weighing 30-400 kg^{5,6,8}.

The research for creating ETMT for ultra-small SSV (nanosatellites) weighing 7-10 kg, assuring margin of characteristic speed up to 60 m/s, is being conducted at the present moment³.

Concept of action of the designed ETMT with THE with energy consumption more than 60 W is based on pre gasification of anhydrous ammonia in propulsion system's evaporator and final ammonium dissociation in ETMT and decomposing in hydrogen and nitrogen⁴. The usage of evaporator for gasification of liquid ammonium results in the increase of energy consumption of CPS as part of SSV.

For this reason, for SSV, particularly, of ultra-low mass (under 10 kg) with tight energy supply, the objective is to eliminate an autonomous evaporator by developing ETMT with the scheme combined with the evaporator functioning as liquid fuel evaporator and gas fuel heater.

Furthermore, ETMT with THE, located inside and contacting with fuel, require sealing of terminals and thermocouples exit points by a special sealant. This operation is technologically labour-intensive and time-consuming (up to 10 days).

ETMT with THE advantage is the possibility of THE reservation (constructively ETMT is manufactured with the main and the back up THE).

When using ETMT, the objective is to find the compromise between the cost of thrust and the specific burst of power. The specific characteristics of ETMT depend on the starting method of CPS – “hot” or “cold”. During the “cold” starting method, ammonium, preliminarily gasified in the evaporator, is conducted to ETMT; simultaneously the heaters of ETMT are started. The “hot” starting method includes preheating of the construction with the help of regular heaters and the following feeding of ammonium, preliminarily gasified in the evaporator, to ETMT⁴.

Operating experience of ETMT with THE showed that due to reliability conditions, less energetically beneficial cold start method is used.

The alternative, excluding the listed disadvantages of ETMT with AHE, is ETMT with AHE^{1,2}. ETMT with AHE makes the “hot” starting method possible and thereby increases specific burst of power. ETMT with AHE studies are of interest for the purposes of creation of CPS for manoeuvrable SSV, particularly of ultra-low mass under 10 kg (nanosatellites).

2. Literature Review

Among the manufacturing companies of ETMT for SSV in a broad range of masses, it is important to mention the Surrey Space Centre (Surrey Space Centre, University of Guildford, and Surrey County, Great Britain). Various microthrusters are designed by SSTL company, including Mark-III with energy consumption under 100 W. Microthrusters of this type are used on SSVUoSAT 12 and UK-DMC¹²⁻¹⁴.

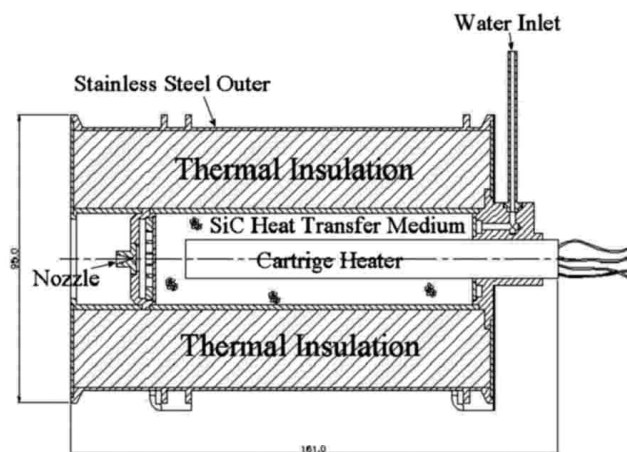


Figure 1. Mark-III, Mark-IY microthrusters diagram.

These microthrusters can be classified as ETMT with AHE (Figure 1).

Fuel ($H_2O/N_2/N_2O$ /methanol/He) goes to the annular space between AHE and the casing, where it is heated. The heat energy gain is transformed to the motional energy of gas outflow from nozzle.

At specific burst of power of 127 s, thrust 93 mN (9.5 gs) and power consumption of 90 W, the microthruster provides total increment of velocity UoSAT 12 of 10.4 m/s.

SSVUoSAT 12 contains 2.5 kg of nitrogen oxide (sufficient for 14 hours of microthruster operation). CPS contains working medium feed gas-pressure system, designed by the university in cooperation with Polyflex Aerospace company located at Cheltenham, Great Britain.

Steam engine with thrust of 300mN, successfully flight tested, was included into meteorological SSV UK-DMC.

Engineering company SSTL claims that in comparison with gas-jet nozzles, using nitrogen as a working medium, steam microthrusters have higher value of specific burst of power and superior mass characteristics. In addition, they are environmentally friendly and do not require tightened security measures during pre-flight training.

Power consumption of the designed CPS is 3W, which is used for the working medium heating up to 473°K. The obtained steam is released through the jet-pipe nozzle. In the course of flight tests, the microthruster has been working at the nominal thrust rating during 30 s, consuming around 2 g of water.

SSTL company is planning in the long term to use similar microthrusters as regular actuating devices of position control system and stabilization of nanosatellites under 10 kg.

The microthruster in the Figure 2 relates to ETMT with AHE⁹.

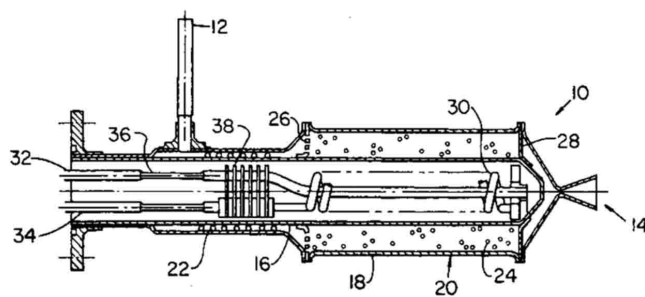


Figure 2. Microthruster diagrams per US4608821. A patent 14 – De Leval nozzle; 16-chamber; 20-annularchamber; 30-heatingelement; 32,34-terminals.

The chamber with the heating element is isolated from the annular chamber, connected with fuel feed system and de Laval nozzle.

Short period of fuel contact with AHE resulting in decreasing of specific burst of power of ETMT, is a disadvantage of the specified microthrusters.

3. Method and Materials

By its structural design ETMT with AHE are specialized for the creation of low-orbiting manoeuvrable SSV of various application with Correcting Propulsion Systems (CPS), particularly for ultra-small SSV with limited capacity of energy consumption system.

ETMT with THE with thrust 30 mN, 40 mN, 50 mN were designed for experimental tests.

As a method of choice of the basic diagram of ETMT with AHE with different thrusts, a multi-purpose approach was used, according to which the structure of ETMT is represented as a set (Figure 1):

$$\text{SETMT: (SB} \times \text{SC)} \quad (1)$$

where, - SB is structural parameters forming the base structure, used for the construction of ETMT with thrusts 30,40 and 50 mN;

- SC – structural parameters forming component structures used together with the base structure for the construction of ETMT with thrusts 30, 40 and 50 mN.

In accordance with (1) experimental samples of ETMT with AHE were made and experimental tests were carried out in the vacuum chamber conditions with the use of nitrogen as working medium (Figure 3-5).

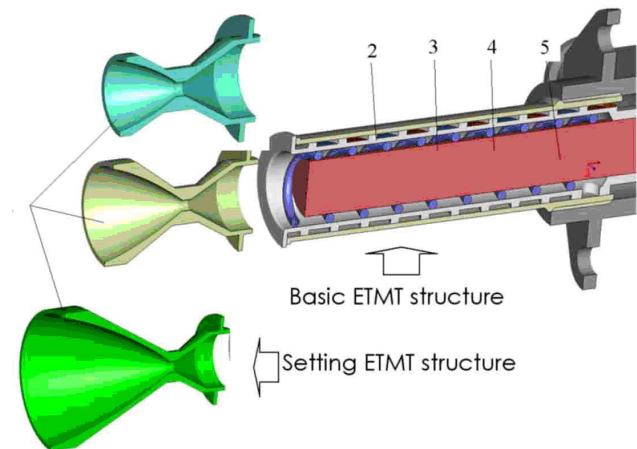


Figure 3. Shaping diagram for ETMT with basic and setting structures with contoured nozzles with different thrust. Setting structure: 1 – Changeable nozzles at 30,40,50 mN; Basic structure: 2 – outer case; 3-internal case with gas passages in the form of double-start thread; 4-gas flow conditioner; 5-AHE.

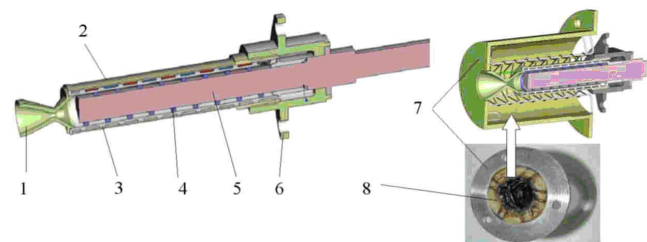


Figure 4. General view of ETMT with autonomous heating element with contoured nozzles and its installation in a heat-protective cover. 1 – nozzle; 2 – outer case; 3 – internal case with gas passages in the form of double-start thread; 4 – gas flow conditioner; 5 – AHE; 6 – microthruster attachment point; 7 – heat protective cover; 8 – heat insulation.

In the function of AHE, an electric heater with two thermocouples is used with characteristics: Continuous rating – 60 W; operating voltage – 12 V; diameter– 6.0 mm; length – 80 mm; mass – 0.03 kg.

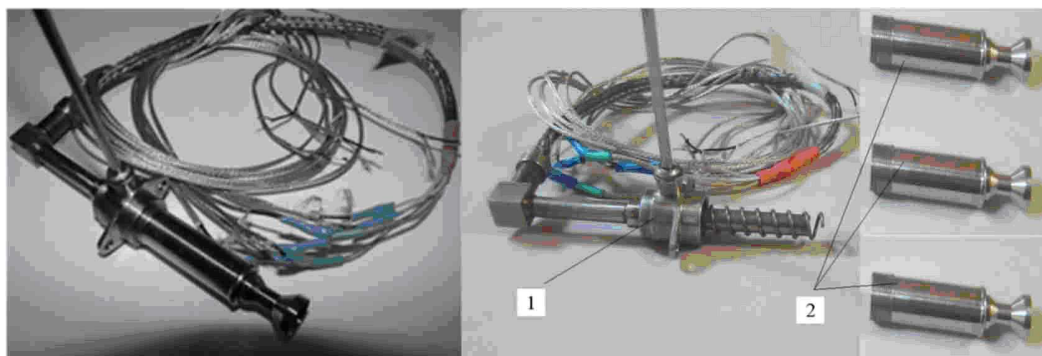


Figure 5. Component elements of experimental samples of ETMT with AHE with 30, 40, 50 mN thrust. 1 – AHE assembled with the control agent retrieving system and the gas flow conditioner; 2 – ETMT nozzles with outer and internal cover.

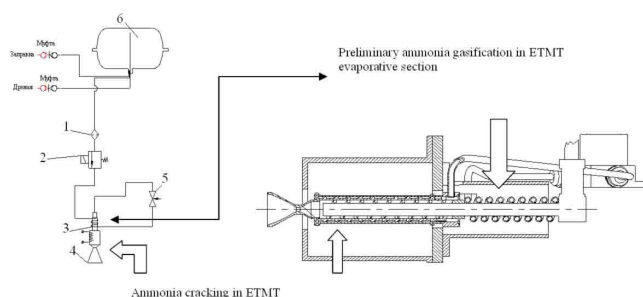


Figure 6. Ammonia cracking diagram in ETMT with preliminary ammonia gasification in ETMT evaporative section. 1 – filter; 2 – electric valve; 3 – ETMT evaporative section; 4 – ETMT; 5 – MRV; 6 – ammonia container.

The special feature of ETMT with AHE is a possibility of the hot starting method, requiring ETMT preheating before feeding of the working medium. Hot starting method in comparison with cold starting method allows increasing of ETMT specific burst of power using allocated power consumption as a part of CPS.

Allocated power consumption for CPS is used for the automatic equipment functioning, ammonium gasification in CPS evaporator and final ammonium dissociation in ETMT.

Method, based on the increase of power of the final ammonium dissociation in ETMT by means of gasification and final ammonium dissociation from the single source of power – AHE of ETMT, is suggested to increase ETMT specific burst of power as part of CPS. In this case, ETMT with AHE with the scheme combined with evaporator is present.

Basic circuit and embodiment of experimental ETMT and AHE⁷ with diagram combined with the evaporator are shown in Figure 6 and 7.

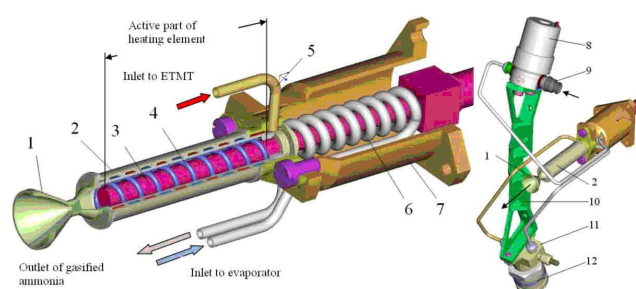


Figure 7. Plain view and structural design of experimental ETMT with diagram combined with the evaporator. 1 – nozzle; 2 – case with gas passage; 3 – AHE; 4 – vortex generator; 5 – lead pipe; 6 – evaporator in the form of rolled tube; 7 – heat protective cover; 8 – electric valve; 9 – filter; 10 – bracket support; 11 – controlled throttling device; 12 – pressure sensor.

The feed system of gasified fuel in experimental ETMT is made in form of a coiled pipeline, located on the case of AHE and contacting with it, its inlet fitting contains junctions with liquid gasifying fuel feed system, and outlet fitting is assembled with the blast tube of the microthruster through the pressure reducing and survey system.

The designed experimental ETMT with AHE with the scheme combined with evaporator can operate in a wide range of electrical capacities under 60 W. The construction of ETMT with the scheme combined with evaporator for CPS as part of nanosatellites with allocated power of 8-15 W is connected with the development of a small-size AHE providing quicker starting operation to the ETMT steady mode and increase of stationery temperatures of fuel heating in ETMT.

The undertaken study showed that the outer diameter of the cylindrical part of the heating element with power

capacity of 8-15W should not be more than 3 mm with the wall thickness of 0.3-0.5 mm.

Figure 8 and 9 show the versions of ETMT structural design with the scheme combined with evaporator with small-size AHE and possibility of a regulated choke device plugging-in.

This configuration of ETMT AHE is made of nichrome wire in an electroinsulating casing of silica fibre, impregnated by heatproof adhesive composition. Filament heater has a form of a double spiral, coiled around the case of thermocouple with electroinsulating coating.

Both AHE with one spiral (unreserved AHE), as well as with double spiral, positioned in parallel to each other (reserved AHE), are possible. Coil span of the wire heater on the evaporative section may differ. It is chosen basing

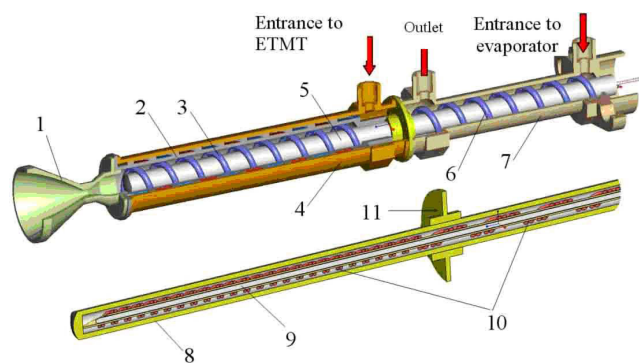


Figure 8. ETMT plain view with diagram combined with the evaporator with small scale AHE 1 – nozzle 2 – gas passage; 3 – ETMT vortex generator; 4 –ETMT case; 5 – small scale AHE with 3 mm dia; 6 – vortex generator of the evaporator; 7 – evaporator case; 8–heater case; 9 – thermal couple case; 10 –AHE nichrome wire; 11 – flange.

on the solution of the optimization problem for peak heating of the gasified fuel.

AHE is placed inside a thin-wall case, electroinsulating coating is applied on its inside surface. The filling is used for better heat transfer from the wire heater to the outside surface of the case.

4. The Results of the Land Experimental Tests of Electrothermal Microthrusters with Autonomous Heating Elements

The experimental tests of ETMT with AHE were carried out both with the use of working medium (nitrogen, air), as well as without – in a vacuum chamber under a clear dome in accordance with Figure 10.

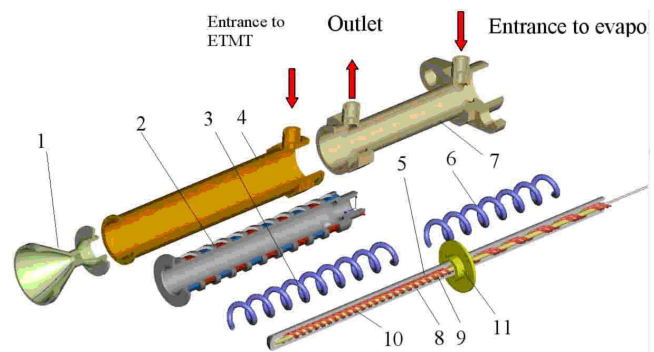


Figure 9. ETMT component parts with diagram combined with the evaporator with small scale AHE.



ETMT installation in a vacuum chamber

ETMT



Heat protective cover

Figure 10. Installation of ETMT with AHE in a vacuum chamber.

Tests items:

- Experimental ETMT with AHE with thrusts 30, 40, 50 mN;
- Experimental ETMT with AHE with the scheme combined with evaporator.

The tests of defining the heat and cooling dynamics of ETMT configuration with thrust 30 mN and supply power of 40, 50, 60 W were carried out to confirm the possibility of the hot starting method of ETMT (Figure 11).

The use of supply power of 40-60 W is characteristic for ETMT as part of CPS for SSV weighing 50-400 kg. The power capacity for SS Vallocated for ETMT weighing under 50 kg and tight energy supply is considerably limited.

Therefore, the study of the thermal value of ETMT configuration with thrust of 30 mN and supply power of 3.75-33.75 W was undertaken (Figure 12).

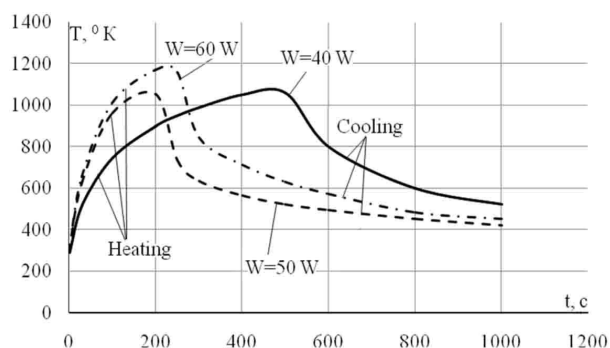


Figure 11. Dynamics for cooling and heating of ETMT with AHE with 30 mN thrust without control agent supply.

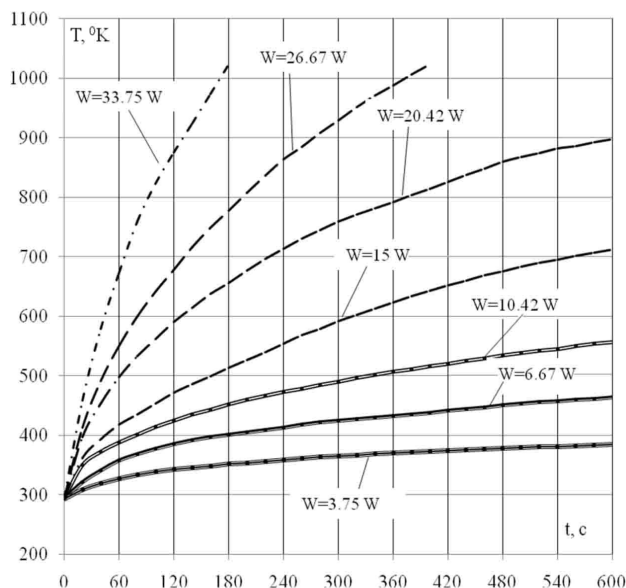


Figure 12. Changing of ETMT heating temperature in time.

The obtained data shows that the time of ETMT pre-heating before fuel feeding is defined considerably by the power consumed by ETMT. There were no burnouts during the tests. This confirms the possibility of the hot starting method of the ETMT with AHE.

The temperature during the tests of ETMT with AHE with nitrogen discharge was maintained at 1073 °K. The ETMT power sensitivity to nitrogen flow is shown in Figure 13.

The experimental tests of ETMT with AHE with thrust 40, 50 mN were carried out in order to study the temperature characteristics of ETMT with AHE at different flows and power consumption.

The following results of heating dynamics for ETMT with AHE with thrust 40 mN and diameter of the nozzle throat section of 1.4 mm were obtained (T_{heat} - construction heating temperature, °K; W - power, W; τ_{ETMT} - ETMT heating time, s):

- Heating at $\tau_{\text{ETMT}} = 270\text{s}$ at $W = 20.79\text{ W}$: $T_{\text{heat}} = 643^\circ\text{K}$;
- Heating at $\tau_{\text{ETMT}} = 380\text{s}$ at $W = 41.8\text{ W}$: $T_{\text{heat}} = 1073^\circ\text{K}$.

The change of stationery temperature of ETMT with thrust 40 mN in relation to heating power at nitrogen discharge of 29.58 mg/s is shown in Figure 14.

Figure 15 shows stationary temperature dynamics of ETMT with thrust 40 mN in relation to nitrogen discharge at heating power of 68.60 W.

The following results of heating dynamics for ETMT with thrust of 50 mN and 1.52 mm diameter of the nozzle throat section were obtained:

- Heating at $\tau_{\text{ETMT}} = 270\text{s}$ at $W = 20.79\text{ W}$: $T_{\text{heat}} = 603^\circ\text{K}$;
- Heating at $\tau_{\text{ETMT}} = 230\text{s}$ at $W = 41.8\text{ W}$: $T_{\text{heat}} = 853^\circ\text{K}$.

Stationary temperature dynamics of ETMT with thrust 50 mN in relation to the heating power at nitrogen discharge of 29.58 mg/s is shown in Figure 16. Figure 17 shows stationary temperature dynamics of ETMT with thrust 50 mN in relation to nitrogen discharge at heating power of 71.05 W.

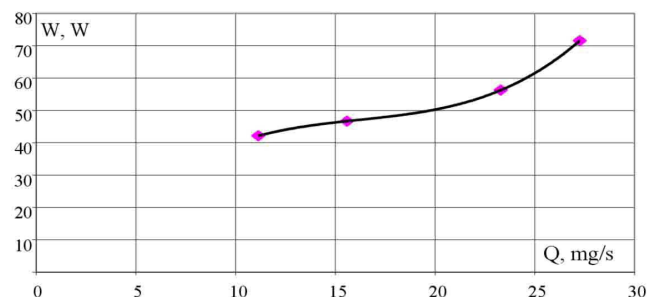


Figure 13. Dependence of ETMT power on nitrogen expd. at providing nitrogen temperature at the level of 1073°K.

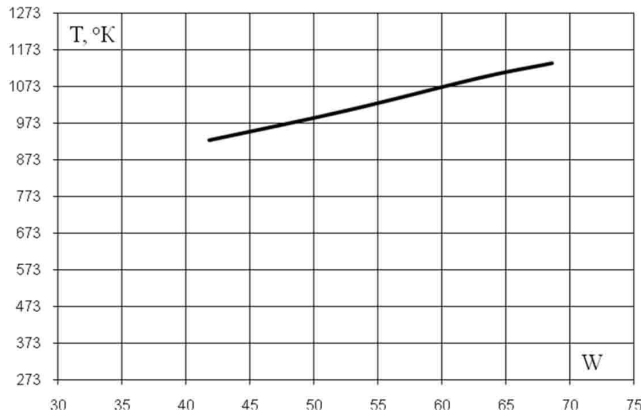


Figure 14. Changing of stationary temperature of ETMT with AHE with 40 mN thrust depending on the heat capacity.

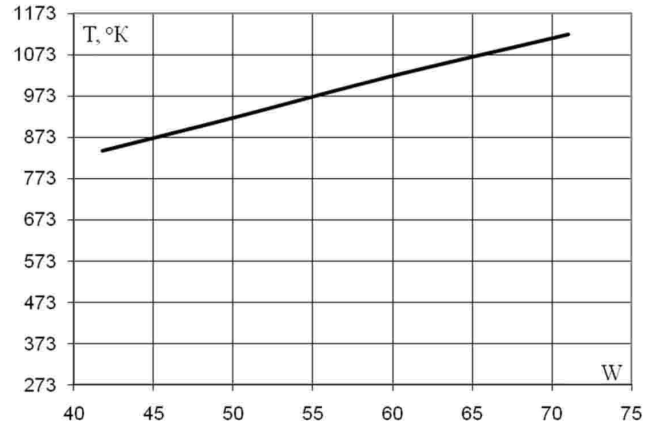


Figure 16. Changing of stationary temperature of ETMT with AHE with 50 mNv thrust versus heating capacity.

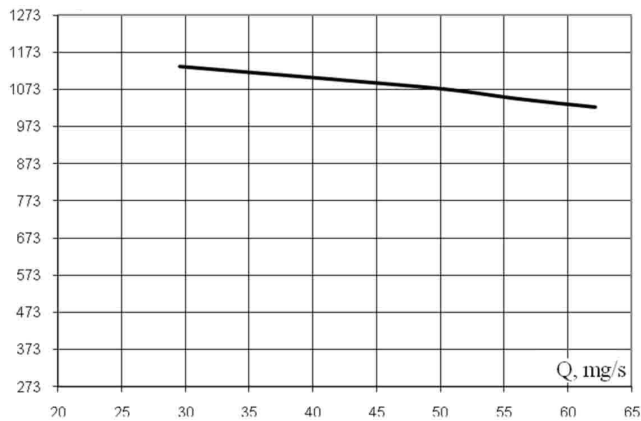


Figure 15. Changing of ETMT stationary temperature with 40 mN thrust versus nitrogen expd.

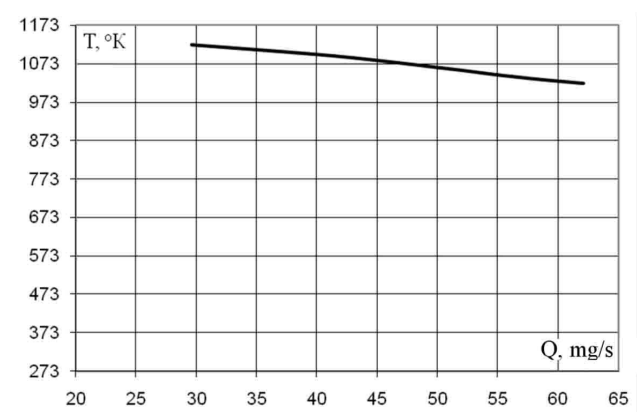


Figure 17. Changing of stationary ETMT temperature with AHE with 50 mN thrust versus nitrogen expd.

The working capacity of ETMT with AHE in a wide range of power capacities allows its use for the construction of CPS for SSV weighing under 10 kg (nanosatellites). In this regard, the heating tests of ETMT with the scheme combined with evaporator were carried out at cold and hot starting methods with the use of air as working medium (Figure 18).

Figure 19 shows the test results of AHE and ETMT casing temperatures. Figure 20 shows the test results of temperature dynamics of the case and the heating element of ETMT with AHE with the scheme combined with evaporator with respect to time for different power consumption at hot starting method (gas feeding from 10 min. to 15 min.)

The obtained data indicates the possibility of ETMT with AHE construction for a nanosatellite, generated for CPS at power under 15 W.

5. Evaluation of the Test Results

The undertaken study showed:

- The use of a multi-purpose approach allows constructing of ETMT with AHE with different characteristics due to replaceable conical and bell nozzle linings' usage without changing of ETMT basic design;
- The use of AHE provides higher level of tightness due to welded seams' usage in the construction; alternative ETMT with THE uses a special sealing compound for tightening that is not workable under manufacturing conditions;
- By its properties, ETMT with AHE is competitive to ETMT with THE due to the hot starting method that is more efficient in comparison with the cold starting method.

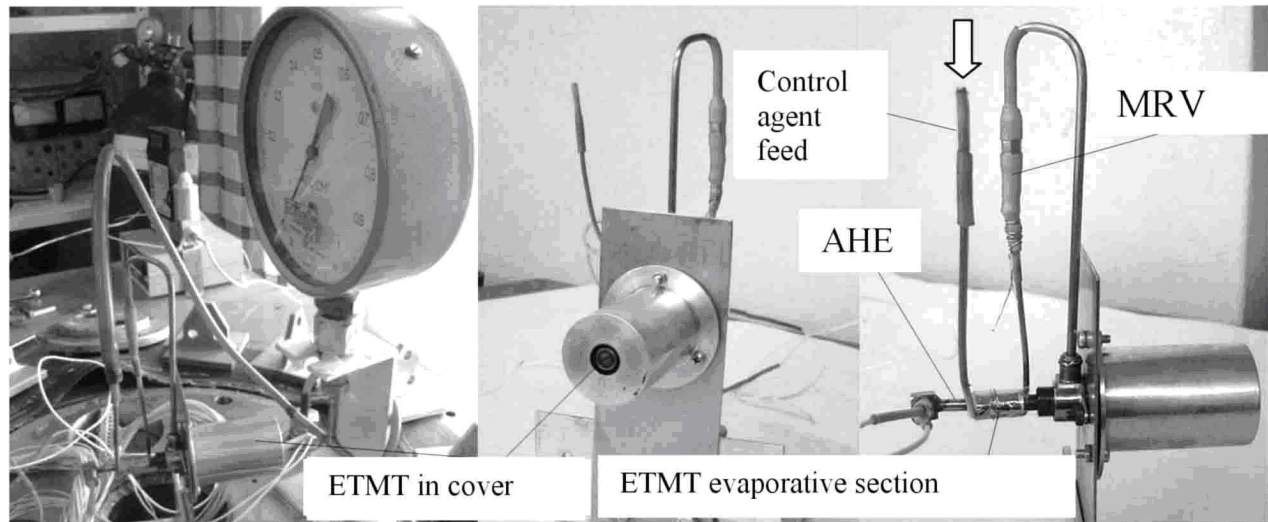


Figure 18. Plain view of experimental ETMT with AHE with diagram combined with evaporator in heat-protective cover.

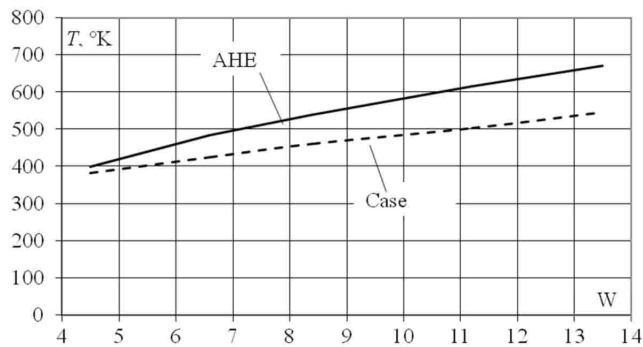


Figure 19. Dependence of the maximum steady temperature of the case and the heating element of ETMT with diagram combined with evaporator from power at cold start.

- Experimental tests of samples of ETMT with thrusts 30, 40 and 50 mN with common AHE with nominal power capacity of 60 W, working voltage 12 V, diameter 6.0 mm, length 80 mm, mass 0.03 kg showed its working capacity in a power range from ≈ 4 W to 71 W, including usage of the hot starting method;
- ETMT with AHE can serve the purpose as part of CPS for nanosatellites with allocated power capacity under 15 W;
- Follow-on development of ETMT with AHE is connected with the construction of ETMT with the scheme combined with evaporator and performance enhancement of AHE;
- ETMT with AHE with the scheme combined with evaporator allows increasing of specific burst of power by 30–35 % due to the increase of ETMT power

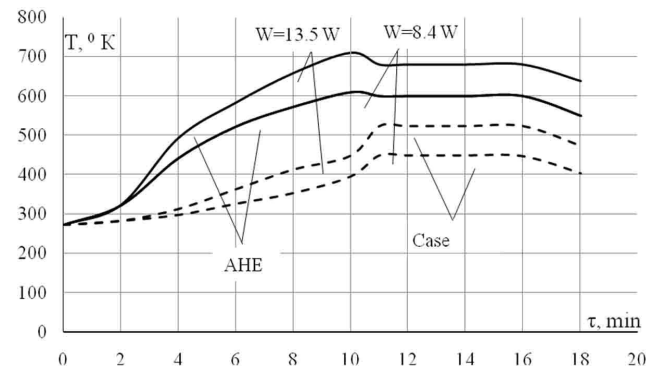


Figure 20. Changing of the temperature of the case and the heating element ETMT with AHE with diagram combined with the evaporator depending on the time for various intake power rates at hot start (gas feeding from minute 10 to minute 15).

consumption within the limits of the allocated power consumption as part of SSV;

- For ETMT with AHE with the scheme combined with evaporator the outside diameter of a cylindrical part of AHE with nominal power capacity 8–10 W should not exceed 3 mm with wall thickness not more than 0.3–0.5 mm.

Experimental test results' evaluation shows that the starting stabilization operation of ETMT with AHE to the standard temperature conditions is characterized by different heating time of the construction at power capacity levels specified. Thus, for ETMT with thrust of 30 mN:

- At electrical power capacity of 40 W supplying AHE, temperature $T_{\text{heat}} = 1060^{\circ}\text{K}$ is obtained at $\tau_{\text{ETMT}} = 500$ s;
- At electrical power capacity of 50 W supplying AHE, temperature $T_{\text{heat}} = 1052^{\circ}\text{K}$ is obtained at $\tau_{\text{ETMT}} = 180$ s;
- At electrical power capacity of 60 W supplying AHE, temperature $T_{\text{heat}} = 1190^{\circ}\text{K}$ is obtained at $\tau_{\text{ETMT}} = 240$ s.

Experimental tests of ETMT with AHE with thrust 40, 50 mN were carried out in order to study temperature characteristics of ETMT with AHE at different discharges and power consumption.

The following results were obtained for ETMT with AHE with thrust 40 mN and 1.4 mm diameter of nozzle throat section:

- At power consumption $W = 20.79$ (41.8) W the ETMT heating temperature without gas feed is $T_{\text{heat}} = 643$ (1073) $^{\circ}\text{K}$, heating time $\tau_{\text{ETMT}} = 270$ (380)s;
- While changing the power consumption $W = (41.8-68.6)$ W at gas flow $Q = (29.58-62.13)$ mg/s the stationary temperature change is $T_{\text{heat}} = (953-1133)^{\circ}\text{K}$;
- For fixed-rate gas flow $Q = 29.58$ mg/s at changing of power consumption $W = (41.8-68.6)$ W the change of stationary gas temperature is $T_{\text{heat}} = (928-1136)^{\circ}\text{K}$.
- The following results were obtained for ETMT with AHE with thrust 50 mN and 1.52 mm diameter of nozzle throat section:
- At power consumption $W = 20.79$ (41.8) W the ETMT heating temperature without gas feed is $T_{\text{heat}} = 603$ (853) $^{\circ}\text{K}$, heating time $\tau_{\text{ETMT}} = 270$ (230)s;
- While changing the power consumption $W = (41.8-68.6)$ W at gas flow $Q = (29.58-62.13)$ mg/s the change of stationary temperature is $T_{\text{heat}} = (843-1123)^{\circ}\text{K}$;
- For fixed-rate gas flow $Q = 29.58$ mg/s at changing of power consumption $W = (41.8-71.05)$ W the change of stationary gas temperature is $T_{\text{heat}} = (840-1123)^{\circ}\text{K}$.

The study of the thermal value of the construction of ETMT with AHE with thrust 30 mN in order to design ETMT with the scheme combined with evaporator and hot starting method has found that:

- At power consumption of ≈ 10 W in the heating time range $\tau_{\text{ETMT}} = (20-600)$ s the heating of ETMT is obtained up to $T_{\text{heat}} = (350-556)^{\circ}\text{K}$;
- At power consumption of ≈ 20 W in the heating time range $\tau_{\text{ETMT}} = (20-600)$ s the heating of ETMT is obtained up to $T_{\text{heat}} = (397-897)^{\circ}\text{K}$;

- At power consumption of ≈ 42 W in the heating time range $\tau_{\text{ETMT}} = (20-100)$ s the heating of ETMT is obtained up to $T_{\text{heat}} = (513-1013)^{\circ}\text{K}$;
- At power consumption of 60 W in the heating time range $\tau_{\text{ETMT}} = (20-40)$ s the heating of ETMT is obtained up to $T_{\text{heat}} = (651-923)^{\circ}\text{K}$.

The obtained data shows the possibility of ETMT with AHE usage both as an evaporator and as a working medium heater in a wide range of power consumption. ETMT with AHE with the scheme combined with evaporator can be used for CPS as part of SSV of wide range of masses, including nanosatellites.

Test results of ETMT based on AHE with the scheme combined with evaporator for nanosatellites CPS show:

- For the cold starting method at power consumption of $W = (4.5-13.5)$ W the peak steady temperature of AHE is $T_{\text{AHE}} = (400-670)^{\circ}\text{K}$, of the case - $T_{\text{case}} = (381-545)^{\circ}\text{K}$;
- For the hot starting method at power consumption of $W = 8.4$ W the peak steady temperature of AHE is $T_{\text{AHE}} = 600^{\circ}\text{K}$, of the case - $T_{\text{case}} = 450^{\circ}\text{K}$;
- For the hot starting method at power consumption of $W = 13.5$ W the peak steady temperature of AHE is $T_{\text{AHE}} = 680^{\circ}\text{K}$, of the case - $T_{\text{case}} = 523^{\circ}\text{K}$.

The undertaken study proves the possibility to obtain high specific performances of ETMT with AHE.

6. Conclusions

1. ETMT with AHE is a competitive microthruster among the existing ones, and as part of CPS of SSV, provides:
 - Increase of ETMT specific burst of power by 15-20 % due to the hot starting method of a microthruster;
 - High level of tightness of a microthruster;
 - Processability of the construction and, consequently, cost reduction for its production.
2. Obtained data of the experimental study of ETMT with AHE for CPS shows that they fully satisfy the requirements of manoeuvrable SSV in a range of its mass characteristics: 10–400 kg in the field of orbital manoeuvring problem solving.
3. Based on the results of the undertaken experimental study the design-basis appearance of ETMT with AHE is defined, ETMT temperature and dynamic

characteristics are evaluated and ways of further construction improvement are suggested.

4. Basing on the results of the project design study of ETMT with AHE it is possible to conclude that there is a technological gap allowing the possibility of ETMT construction for SSV.
5. A whole range of structural-and-technological facilities in the field of ETMT with AHE have been produced and tested under experimental conditions;
 - ETMT with thrusts 30, 40 and 50 mN in a range of power capacities from ≈ 4 W to 71 W, including the usage of the hot starting method;
 - ETMT with AHE with the scheme combined with evaporator, allowing the increase of specific burst of power by 30–35 % due to abandoning of CPS evaporator and increase of ETMT power consumption;
 - ETMT with the scheme combined with evaporator for SSV nanosatellites.
6. The undertaken experimental study of ETMT with AHE shows that the obtained level of specific burst of power, determining SSV fuel capacity can reach 230–250s at microthruster power consumption of 60 W. The given metrics correspond to the tendencies of the international development level of CPS for SSV.
7. Follow-up development of ETMT with AHE is connected with the creation of AHE with diameter max 3 mm and wall-thickness of 0.3–0.5 mm.
8. The use of a multipurpose approach allows the creation of different ETMT with AHE with a high level of standardization that enhances reliability of their performance, and reduces time and cost for their manufacturing.

7. Acknowledgements

The work within the present research is implemented with financial support from Ministry of Education and Science of Russia in the course of performance of the agreement for granting No. 14.574.21.0104 dated 08.09.2014.

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