Study of power-to-weight ratio of the electrothermal propulsion system of nanosatellite maneuvering satellite platform

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Abstract. The direction of the solution of the actual task of maneuvering satellite platforms (MSP) design for nanosatellite weighing up to 10 kg, power-to-weight ratio of PS up to 8 W(electrothermal micro engine (ETME) 5 W, vaporizer 2 W, electrovalve up to 1 W) and with characteristic velocity up to 60 m/s were considered on the basis of studies of the propulsion system (PS) with ETME. The aim of study is the confirmation of technical possibility of nanosatellites design with mass up to 10 kg, power-to-weight ratio up to 8 W and with characteristic velocity up to 60 m/s on the basis of PS prototype experimental studies. In the course of the research tasks were solved to determine the design of PS and ETME of nanosatellite's MSP, determine the electric parameters of PS depending on power consumption that determining specific impulse of ETME, and estimate the implemented characteristic velocity of the nanosatellite. The PS constructive scheme of nanosatellite mass of 10 kg was design, PS experimental prototype was produced and PS experimental research on ammonia were conducted. The 200°C was reached per 900 s at 5 W ETME power consumption with nitrogen, that equivalent to specific impulse of ammonia ETME 124/136 s when entering the stationary mode. 2 W energy consumption of a two-thread liquid ammonia vaporizer is experimentally substantiated. The using of electrovalve stepped control cyclogram allowed to reduce the average power consumption to 1 W.

1. Introduction

At present, the relevance of MSP with ammonia PS design is becoming increasingly important, as modern nanosattelites are designed for solving of a wide range of task, including the tasks of orbital maneuvering: Elimination of orbiting errors of nanosatellite by rocket launch vehicles, maintenance of orbital parameters, interorbital maneuvering, construction of orbital groups of nanosatellites and MSC, retraction of the nanosatellite into the orbit of utilization. There are also a number of specific application and scientific tasks: inspection of other MSC and orbital objects, monitoring of Earth outer space, space objects removal into the orbit of burial, etc. [1-3].

The using of ammonia PS in nanosatellites is due to the possibility of obtaining high values of the specific impulse of ETME with minimal energy consumption. This leads to a reduction in the mass of fuel expended on the implementation of a given characteristic velocity of the nanosatellite as part of the orbital manoeuvres as well as the mass of the PS and its means of adaptation to nanosatellite.
The recently created ammonia PS with ETME were part of the "Ugatusat" MSC (Russia, 2008) weighing 35 kg and "BX-2" MSC (China, 2016) weighing 47 kg. These ammoniac PS can be considered as analogues of PS for nanosatellites.

In the MSC "Ugatusat", the weight of the fueling ammonia was 0.4 kg, the power consumption of the ETME was 30 W. The automatic control system include: electrovalve, vaporizer, reducer, fueling and drainage clutch.

Vaporization of ammonia is accomplished by preliminary gasification of ammonia in the vaporizer and final heating in the ETME. PS thrust is 30 mN, specific impulse up to 200 s [1].

In PS of MSC "BX-2" vaporization of ammonia was realized due to the heating of ammonia by solar radiation. Vaporizer, separator and reducer were introduced in PS design. PS thrust is 85 mN, specific impulse is 100 s.

In Ukraine the ammonia PS were designed for MSC "Sich - 2M" (2011-2012) and MSC "Microsat".

At the stage of maneuvering nanosatellite designing, while limiting its mass with the realization of a adjusted characteristic velocity, the task is to redistribute a adjusted mass to the maximum possible mass of PS and the minimum possible mass of electronic components and the design of a nanosatellite.

In turn, the mass of the PS is redistributed to the maximum possible mass of fueling ammonia and the minimum possible mass of the design of the PS.

This approach to the design of ammonia PS leads to a failure to reserve elements of the pneumohydraulic system of PS and to the use of a highly reliable "cold" ETME switching scheme.

A mass-related problem is the choice of optimum nanosatellite power supply from the condition of obtaining a adjusted characteristic velocity.

The costs of the characteristic velocity for the implementation of typical orbital maneuvers of a nanosatellite weighing 10 kg can be:

- Elimination of launch errors (inclination of the orbit, period of rotation and altitude) - 12 m/s;
- sustaining a lifetime of 1 year in a circular orbit 600 km, 700 km - 3 m/s, 1.1 m/s;
- a maneuver from a circular orbit 600 km to 650 km - 27 m/s;
- move into orbit of utilization with the lifetime of 25 years from a circular orbit of 700 km - 31 m/s.

Analysis of the costs of the characteristic velocity indicates that the choice of the tasks of the orbital maneuvering of the nanosatellite should be carried out based on the capabilities of the nanosatellite in terms of the available reserves of the characteristic velocity, taking into account the power supply limitation.

For example, the CAN-X4 nanosatellite (Canada) has a characteristic velocity margin of only 14 m/s at a mass of 7 kg. The power supply system of the nanosatellite provides a "peak" power input of up to 10 W.

The nanosatellite is built on Sel's Generic Nanosatellite Bus platform. The platform has a cubic shape with a side of 20 cm and is equipped with CNAPS PS.

The CNAPS PS force module has a size of 18×12.5×7 cm. As a working fluid, liquid sulfur hexafluoride is fed from two tanks with a capacity of 300 ml each.

The working body is vaporized and discharged through four nozzles, controlled independently. The specific impulse of the nozzle is 35 s.

When the nanosatellite's dimensions are limited, the fuel reserves are determined by the layout of the MSP with PS and ETME.

In accordance with figure 1 shows the configuration of PS with ETME according to the classical scheme, in which the fuel tank of PS is cylindrical with torosferic bottoms, and the ETME is located near the tank. This layout increases the size of the PS by the length of the ETME.
Figure 1. The PS layouts of the classical scheme: 1 – fuel tank; 2 – ETME.

The length of the ETME is determined by the layout of its heating zone and the current outputs zone. With their co-axial arrangement, the length of the ETME is maximized (Figure 2). The reduction of the length of ETME is obtained in the T-shaped layout of the heating zone and the current outputs zone (Figure 3). The greatest length has an ETME with a circuit matched with the vaporizer. In this ETME, the functions of the ETME and the vaporizer of a working fluid are implemented in one structure (Figure 4) [1, 4, 5].

Figure 2. ETME scheme with coaxial arrangement of the heating zone and the zone of the current collectors: 1 – the profiling nozzle; 2 – Hull; 3 – internal hull with gas lines; 4 – gas flow generator; 5 – heater; 6 – attachment point of the microengine; 7 – heater flange.

Figure 3. ETME with a T-shaped arrangement of the heating zone and the zone of the current collectors: 1 – the profiling nozzle; 2 – tubular heating element (main and reserve); 3 – hull; 4 – a barrel with a collar; 5 – gas pipeline; 6 – thermocouple; 7 – the body of the current collectors.

Figure 4. General view of the ETME scheme combined with the vaporizer: 1 – is the nozzle; 2 – gas pipeline; 3 – swirler of ETME; 4 – ETME hull; 5 – heater; 6 – vaporizer swirler; 7 – vaporizer hull, 8 – heater hull; 9 – single-channel metal tube with thermocouple; 10 – heater; 11 – flange.

Designed ammonia ETME with a thrust of 30 mN are characterized by a thrust price of up to 2 W/mN and are used in a number of MSC with a mass of 30-120 kg. The specific impulse of such
ETME at a power consumption of 60 W does not exceed 250 s. Their circuit design with appropriate modifications allows them to be used as part of a PS for a nanosatellite [4, 5].

The developed ETME for small spacecrafts differ in their constructive diversity and in the type of fuels used [5 ± 9]. Often in ETME can use as a working fluid compressed nitrogen, which has environmental safety. A nitrogen-based working fluid is used in the practice of ground-based experimental testing of ammonia ETME, as well as in some flight CPS. So the firm SSTL (Great Britain) for MSC "UoSAT 12" designed an ETMD of the type "Resistojet" with a working fluid of nitric oxide.

In the ETME of the "Resistojet" type, nitrogen oxide is vaporizing by means of an electric heating element receiving power from the batteries of the MSC. With a specific impulse of 127 s, a thrust of 93 mN (9.5 gs) and an energy consumption of 90 W, the ETME provides a total increase in the velocity of the MSC "UoSAT 12" at 10.4 m/s.

In general, energy-consuming elements of the remote control are an electrovalve, an evaporator and an ETME. When designing a PS for a nanosatellite, the task is to reduce the energy consumption of an ETME, an electrovalve and a vaporizer.

One of the important characteristics of remote control is the time of one-time activation. An increase in the duration of one-time activation of the remote control makes it possible to reduce the number of remote control inputs during the development of the working fluid. A critical element in this case is an electrovalve due to possible overheating during operation.

In a number of works, the possibility of creating maneuvering nanosatellites is based on the results of autonomous studies of ETME while the energy consumption ranges of 5 W to 30 W. However, the relevance of the research ETME in the composition of the PS.

2. Formulation of the problem
The task is to determine the ways of designing and improving the design and construction of ammoniac PS with ETME for MSP of nanosatellites.

The methodological basis for the formation of the design and structural appearance of the PS is the multi-purpose method of structural design [5].

At the heart of the accepted methodology for creating ammonium PS for nanosatellite MPS is experimental testing of new technical solutions in conditions meeting safety requirements. Therefore, compressed nitrogen is used instead of toxic ammonia as a modeling working body.

In this connection, the following experimental studies are of practical interest for the purpose of creating a DV for the nanosatellite SMEs:
- electric tests of PS in a vacuum chamber when working on nitrogen;
- autonomous electrical tests of the electrovalve with control of the power consumption at the open and hold modes.

3. Formatting the text
PS was designed by a multi-purpose structural design method, in which the fuel tank is the completing structure of the PS and is developed optimally for a specific target task [1, 5].

The design of the remote control for the nanosatellite ICP is considered under the limitations of the nanosatellite dimensions 200×200×200 mm. When designing the PS, the layout of the increased density was used due to the execution of a toric-shaped fuel tank with the placement of ETME in the internal cavity of the tank (Figure 5).
Figure 5. Scheme of the PS with increased density of the layout for the nanosatellite MSP with ETME with vaporizer: 1 – fuel tank; 2 – ETME with the vaporizer; 3 – throttle assembly; 4 – electro valve; 5 – board with electronic components.

To carry out experimental studies, a PS scheme with a two-pass vaporizer, an electrovalve, a pressure regulator, and an experimental PS sample was designed (Figure 6 – 8).

Figure 6. Scheme of the MSP of a nanosatellite with an increased density of the layout for carrying out experimental studies: 1 – PS; 2 – the hull of a nanosatellite; 3 – a fuel tank; 4 – electro valve; 5 – pressure regulator; 6 – vaporizer; 7 – ETME.

Figure 7. Experimental PS of a MSP of nanosatellite with an increased density of configuration for conducting experimental studies: 1 – filling and drainage coupling; 2 – the hull of a nanosatellite; 3 – a fuel tank; 4 – the rack of the PS; 5 – ETME; 6 – electro valve; 7 – pressure regulator; 8 – electrical connectors.
Figure 8. Experimental ETME: 1 – nozzle; 2 – titanium platinum; 3 – connecting the working fluid; 4 – racks; 5 – thermal insulation; 6 – ETME gas inlet; 7 – current leads (heating element and thermocouple); 8 – self-contained heating element with built-in thermocouple.

The pneumohydraulic circuit is shown in accordance with Figure 9.

Figure 9. Pneumohydraulic circuit of PS: GF – ground filter, DC – drainage coupling; CR – clutch refilling; DT – drainage tube; FT – fuel tank; AF – airborne filter; EV – electro valve; TV – toway vaporizer; PR – pressure regulator; PS – pressure sensor; ETME – electrothermal microengine.

The characteristics of the PS are given in Table 1.
Table 1. PS Characteristics

| №  | Parameter                      | Value            |
|----|-------------------------------|------------------|
| 1  | PS thrust, mN                 | up to 30         |
| 2  | ETME type                     | with self-contained heater |
| 3  | Construction mass, kg         | 2.28             |
| 4  | Pressure in fuel tank, MP     | 1.9              |
| 5  | Fuel tank capacity, l         | 0.917            |
| 6  | Volume of filled working fluid, l | 0.78       |
| 7  | Volume of gas cushion, l      | 0.137            |
| 8  | Average value of ammonia filled, kg | 0.484    |
| 9  | Energy consumption range, W   | 5-30             |

The range of power consumption is assumed equal to 10-30 W and was carried out in order to determine the amount of heat loss of the working fluid (loss of characteristic velocity) at elevated powers of 20-30 W, which are difficult to realize in the nanosatellite power supply system.

The electrical tests of the PS have been carried out for the purpose of research:

− dynamics of heating of ETME and vaporizer without supplying the working fluid under normal atmospheric conditions;
− dynamics of heating of the ETME and the vaporizer without supplying the working medium in the vacuum chamber;
− dynamics of heating of the ETME and the vaporizer with the supply of a working fluid in the vacuum chamber (the "cold" start-up method);
− functioning of the PS in accordance with the cyclogram ("hot" start-up method).

During the research, the bench base of the research laboratory "Propulsion systems of microthrust for small spacecrafts" of OmSTU (Figure 10, 11) was used.

![Figure 10. Experimental stand for PS on air without supply of a working fluid: 1 – experimental sample of PS; 2 – multichannel power supply APS-7205L; 3 – multichannel temperature meter MIT-8; 4 – cooling system; 5 – personal computer.](image1)

![Figure 11. Experimental bench for PS study in a vacuum chamber with a working fluid feed: 1 – hose of the pipeline of supply of working fluid to CPS; 2 – experimental sample of CPS; 3 – vacuum chamber; 4 – balloon with a working fluid (nitrogen).](image2)

To reduce the charging cycles of the PS with nitrogen, a test circuit with a balloon with nitrogen connected to the PS is implemented in accordance with Figure 12.
Figure 12. Scheme of connecting a balloon with nitrogen to the PS:
1 – a balloon with nitrogen; 2, 6, 7 – the valves; 3 – manometer; 4 – reducer; 
5 – the filter; 8 – manometer; 9, 10 – filling couplings; 11 – drain coupling; 
12 – fuel tank of the PS; 13 – the filter; 14 – electrovalve.

A normally closed solenoid valve is used as the shut-off valve for supplying the working fluid of 
the PS. The resistance of the coil of the solenoid R = 160 Ohm, with the nominal voltage corresponding 
to the opening of the valve with full stem lift is 27 V, and the power consumed by the valve is 3.5 W.

Holding the valve in the open state requires a deliberately lower supply voltage, and correspondingly, less power consumption, which reduces the total power consumption of the PS. For this purpose, a step-by-step cycle of switching on the solenoid valve was used, with a short-time supply of a guaranteed valve opening voltage, followed by a step-by-step decrease thereof to the guaranteed confinement in the open state.

The control of the voltage applied to the valve winding was carried out according to the scheme shown in Figure 13.

Figure 13. Principal electrical diagram of the solenoid valve control.

At the inlet of the solenoid valve, a pressure of 1.9 MPa was applied, corresponding to the maximum pressure of the working fluid in the tank. Opening was recorded using a float rotameter, installed after the solenoid valve.

The increase in the operating time of the solenoid valve in the PS can be reached by cooling it with ammonia by contact removal of heat with a screw flow line with ammonia (Figure 14).
Figure 14. Start valve with cooling system: 1 – electro valve; 2 – cooling jacket; 3 – a tube with ammonia; 4 – ammonia inlet from the tank; 5 – vaporizer; 6 – pressure regulator; 7 – ETME; 8 – pressure sensor.

The interaction of the mass characteristics of the nanosatellite, the thrust of the ETME, the specific impulse, the time of operation and the number of ETME(PS) inclusions is described by the expression [1]:

\[
V = -g_{0,1} P_{UD}^{V} \ln \left( \frac{m_{NS} - \frac{P_{ETME}}{P_{UD}} T^{R} (N-1) - \frac{P_{ETME}}{P_{UD}} T^{V} N}{m_{NS} - \frac{P_{ETME}}{P_{UD}} T^{R} (N-1)} \right) + \frac{P_{ETME}}{P_{UD}} T^{R} N
\]

where, \( V \) is the characteristic velocity realized by the PS in the nanosatellite (NS);
\( p_{UD}^{V} \) – the average specific impulse of the ETME when entering the mode;
\( p_{UD}^{R} \) – the average specific impulse of the ETME after entering the mode;
\( m_{NS} \) – start mass of nanosatellite;
\( P_{ETME} \) – ETME thrust;
\( T^{V} \) – time of ETME release to the mode;
\( T^{R} \) – ECMD operating time on the mode;
\( N \) – the number of ETME(PS) inclusions.

4. Results of experiments
Below are the results of studies of the vaporizer and ETME in the composition of the PS, as well as the results of autonomous tests of the PS solenoid valve. The results of the experiments on the temperature of the vaporizer are given in Table 2.

| №  | Characteristic                                                                 | Value          |
|----|-------------------------------------------------------------------------------|----------------|
| 1  | Vaporizer power consumption, W                                                | 2 | 3 | 4 | 5 |
| 2  | Maximum vaporizer temperature when operating under normal conditions without gas, °C | 76.36 | 87.79 | 98.55 | 105.68 |
| 3  | Maximum vaporizer temperature when operating under normal conditions without gas in a vacuum, °C | 120.74 | 142.23 | 150 | 156.17 |
The maximum temperature of the evaporator when operating in vacuum with the supply of a working fluid, °C

|   | Description                                                                 | Value 1 | Value 2 | Value 3 | Value 4 |
|---|-----------------------------------------------------------------------------|---------|---------|---------|---------|
| 4 | The maximum temperature of the evaporator                                  | 89.88   | 101.73  | 110     | 112.3   |
| 5 | The set time for the maximum temperature of the evaporator, s               | 1200    | 1200    | 1200    | 1200    |
| 6 | Dialing time up to 90% of the maximum temperature of the evaporator, s      | 600-800 |         |         |         |

The results on the investigation of the temperature of the ETME under a cold startup scheme are shown in Figure 15 – 17.

**Figure 15.** Dependence of the temperature of the ETME on the heating time at different power supply without gas under normal atmospheric conditions.

**Figure 16.** Dependence of the temperature of the ETME on the heating time at different power supply without gas in a vacuum with a heating temperature limitation of 700 °C.
Figure 17. Dependence of the temperature of the ETME on the heating time at different power supply with gas supply at a cold start-up method in vacuum conditions with a temperature limit of 700 °C.

The resistance of the coil of the solenoid valve used is 160 Ω, while the nominal voltage corresponding to the opening of the electrovalve with a full stem lift is 27 V, and the power consumed by the valve is 3.5 W.

Studies have shown that holding the solenoid valve in the open state requires a deliberately lower supply voltage and lower power consumption, which reduces the total power consumption of the PS. For this, a step-by-step cyclogram of switching on the solenoid valve is used. A short-term supply of a guaranteed valve opening voltage was carried out, followed by a stepwise reduction of it to a guaranteed confinement in the open state.

At the inlet of the solenoid valve, a pressure of 1.9 MPa was applied, corresponding to the maximum pressure of the working fluid in the tank of PS. Opening was recorded using a float rotameter, installed after the solenoid valve.

As a result of the experiment, a cyclogram including the following stages (Figure 18) was obtained:

- the opening voltage of the solenoid valve for a duration of 3 s, with a power consumption of 1.85 W;
- smooth decrease of voltage applied to the solenoid valve, within 7 s, with a decrease in power to the value of the holding of the solenoid valve;
- holding the solenoid valve, with the required duration of the PS, with a power consumption of 0.12 W.

Figure 18. Cyclogram of the solenoid valve
5. The discussion of the results

The considered power capacity of the nanosatellite consists of the energy consumption of the vaporizer, ETME and electrovalve. The main purpose of the vaporizer is gasification of liquid ammonia supplied from the fuel tank. In accordance with Figure 9 the vaporizer is made by a two-pass, which allows gasification of liquid ammonia with minimal energy consumption (Figure 19) [10].

![Figure 19. Two-threaded vaporizer of the liquid ammonia: 1 – heating element; 2, 5 – ammonia inlet / outlet fittings; 6, 7 – external and internal hull; 8 – two-threaded ammonia feed channel; 9 – swirler.](image)

Researches show:

– at the power consumption of the vaporizer is changed from 2 W to 5 W, the maximum temperature of the enclosure is 90 °C - 112 °C;

– The dialing time of 90% of the maximum temperature of the vaporizer is 600 s - 800 s.

In view of the fact that the autonomous heating element of the vaporizer allows the use of a hot start-up circuit (starting before the working fluid is supplied), the vaporizer must be switched on before the ETME is switched on for 600 s - 800 s for its heating. At the same time, the energy consumption of the vaporizer can be assumed equal to 2 W.

Another measure of reducing the power consumption of the PS is the use of ETME combined with the vaporizer scheme (Figure 4). The main considered energy-consuming element of the PS is ETME.

The obtained experimental values of the ETME temperatures for energy consumption of 5 W, 10 W, 20 W, and 30 W made it possible to estimate the specific impulse of the ETME when entering the mode ($p_{1d}^{v}$) and mode ($p_{1d}^{r}$) when operating on nitrogen (table 3).

| № | The specific impulse with Nitrogen, s | ETME energy consumption, W |
|---|------------------------------------|---------------------------|
|   |                                    | 5 | 10 | 20 | 30 |
| 1 | $p_{1d}^{v}$                       | 100 | 105 | 120 | 144 |
| 2 | $p_{1d}^{r}$                       | 105 | 114 | 133 | 164 |

Table 4 shows the calculated specific impulse values of ETME with autonomous heating element and a profiled nozzle with using nitrogen and ammonia.

| № | Temperature, °C | 47 | 127 | 207 | 287 | 367 | 447 | 527 | 607 |
|---|-----------------|----|-----|-----|-----|-----|-----|-----|-----|
| 1 | The specific impulse with Nitrogen, s | 85 | 95 | 105 | 114 | 123 | 131 | 139 | 147 |
| 2 | The specific impulse with ammonia, s | 107 | 122 | 136 | 149 | 161 | 173 | 183 | 194 |
From the table it follows that the use of ammonia is preferable to the specific impulse of the ETME.

The increase in the specific impulse of the ETME is achieved due to an increase in power consumption to 10 W - 30 W. This can be achieved only by increasing the mass of the nanosatellite (by increasing the size and mass of the solar battery - SB). For stationary SB, the specific mass of the SB can reach up to 4.93 kg/m². Let's estimate the expediency of using the energy consumption in a nanosatellite PS 10W - 30W.

As a criterion, we take the realizable characteristic velocity of the PS in the nanosatellite composition of the reduced mass, taking into account the mass of the SB of the considered power (Table 5).

**Table 5.** Dependence of the characteristic velocity on the specific impulse and energy consumption

| № | ETME energy consumption, W | Nanosatellite characteristic |
|---|--------------------------|-------------------------------|
|   | Mass of nanosatellite, kg | ETME specific impulse with ammonia, \( P_{\text{ETME}}^{*}/P_{\text{solar}}^{*} \), s | Working time, TV/TP, s | Mass of ammonia, kg | Nanosatellite characteristic velocity, m/s |
|---|--------------------------|-------------------------------|---------------------|-------------------|-------------------------------|
| 1 | 5                        | 10.0                          | 124/136             |                   | 63                            |
| 2 | 10                       | 10.5                          | 136/149             | 900/300           | 0.484                        |
|   |                          | 11.0                          |                     |                   | 62                            |
|   |                          | 12.0                          |                     |                   | 57                            |
| 3 | 20                       | 12.0                          | 159/196             | 0.484             | 68                            |
|   |                          | 13.0                          |                     |                   | 63                            |
|   |                          | 14.0                          |                     |                   | 58                            |
| 4 | 30                       | 14.0                          | 187/220             |                   | 68                            |
|   |                          | 15.0                          |                     |                   | 63                            |

The analysis showed that the desire to realize on the nanosatellite energy consumption for the PS of 10 W - 30 W does not give significant advantages for the realized characteristic velocity in comparison with the nano-satellite with the mass of 10 kg and the power consumption of the PS of 5 W.

In this regard, in the future, it is necessary to use the power consumption of an ETME of 5 watts. Improving the design of ETME in terms of reducing its mass to increase temperature while limiting energy consumption in conjunction with the producing of ETME by additive technology. Investigations of the power consumption of the solenoid valve showed that when it is held in the open state, the power consumption can be 0.12 W. A step-by-step cyclogram of power control of the solenoid valve can be realized by the onboard control system of the nanosatellite with minimal mass costs.

The use of the obtained cyclogram will reduce the overall power consumption of the PS.

In addition, together with the application of the electrovalve cooling system (Figure 14), the duration of a single switching can be increased by reducing the heat dissipation of the solenoid valve with a reduced power consumption. In practice, to ensure the guaranteed opening and retention of the solenoid valve in the open state, when designing the onboard control system, the magnitude of the control voltages should be increased by 10-20% of those determined during the experiment.

6. **Summary and conclusion**

1. As a result of the experimental studies carried out by the PS, the possibility of designing a nanosatellite maneuvering platform with ammonium PS and ETME was confirmed.
2. The realized characteristic velocity of a nanosatellite with an ammonia PS with an energy consumption of an ETME of 5 W, an vaporizer of 2 W and an electrovalve of less than 1 W is estimated at 63 m/s.

3. The modes of operation of the PS are defined: ETME
- cold start with simultaneous supply of voltage and working fluid (hot start is also possible);
- vaporizer-start by hot scheme with preheating for 600 s - 800 s;
- electrovalve is a step-by-step cyclogram of the voltage supply.

4. Defined constructive ways to upgrading PS:
- the implementation of a toric-shaped fuel tank with the placement of ETME in the internal cavity of the tank;
- the implementation of ETME combined with the vaproizer circuit;
- equipping the solenoid valve with an ammonia cooling system;
- implementation of the vaporizer by two-way scheme;
- production of ECME by additive technology for weight reduction.

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