Demonstration sample research impulse of the propulsion system of nanosatellite

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Abstract. The aim of the research is to determine ways to create a pulse corrective propulsion systems of a maneuvering nanosatellite at the early stages of design when forming its design appearance on the basis of experimental and numerical studies of a demonstration sample with a multifunctional flow-through launch chamber and an micro resistojet of a transverse nozzle placement scheme. A pneumohydraulic scheme of a propulsion system with various chokes of a multifunctional flow-through starting chamber has been developed. Experimental and numerical studies of a demonstration sample of a propulsion system confirmed its operability and the possibility of achieving the specified characteristics by changing the interdependent main design parameters in terms of pressure, temperature, specific thrust pulses, duration of operation in various operating modes, and design parameters of a multifunctional flow-through launch chamber. Based on the results of experimental and numerical studies, a 3D model of an improved pulse propulsion system was developed.

1. Introduction

Currently, the task of creating orbital groups (swarms) of maneuvering nanosatellites (MN) with pulse corrective propulsion systems (PCPS) for solving a wide range of scientific and applied problems is urgent [1].

PCPS with micro resistojet meet the criteria of reliability, cost, simplicity of design, and time of creation. PCPS with micro resistojet have been used in a number of small spacecraft [2-34].

The tested modes of corrective propulsion systems (CPS) operation with micro resistojet thrust up to 30 mN for small spacecraft weighing 30-120 kg are based on long-term single PCPS inclusions. The maximum duration of a single CPS activation in the small spacecraft can be up to 20 minutes or more, which imposes additional requirements for the small spacecraft orientation and stabilization system for parrying CPS disturbing moments [14,15,17-19].

The micro resistojet can be activated either by a sequential CPS start-up scheme with pre-heating of the structure, or by a parallel start-up scheme, when the power supply and fuel to the micro resistojet occur simultaneously. For small spacecraft weighing more than 30 kg with a micro resistojet power consumption of up to 60 W, according to the condition of ensuring the reliability of heating elements (HE), for example, tubular ones, a parallel CPS start scheme is used with simultaneous supply of the working fluid to the micro resistojet [14,17,31-34].

When the power consumption of micro resistojet is up to 12-20 W, a more profitable sequential CPS start scheme with micro resistojet preheating is used. For micro resistojet heating, stand-alone HE
systems are used, which have a simple design and small dimensions. This type of micro resistojet can be used to create CPS MN [18,19].

When creating PCPS for MN weighing up to 8 kg, we consider the pulse mode of PCPS operation with a duration of one-time activation of micro resistojet less than 1 s with the implementation of the maximum micro resistojet thrust of at least 100 mN. Let’s assume that when forming the design image of a PCPS, the following specified characteristics are used as constraints:
- speed increment MN at one-time PCPS: \( \Delta V = \Delta V_{\text{rad}} \leq 0.01 \text{ m/s} \);
- total characteristic speed of the PCPS in the MN: \( V_{\text{char}} = V_{\text{char}}^\text{2nd} = 100 \text{ m/s} \);
- PCPS weight: 8 kg;
- dimensions of the PCPS: 2U format.

For the considered MN weighing 8 kg in the 6U format, the maximum dimensions of the PCPS are limited to the size of 2U (100x100x200) mm, which poses an urgent task of reducing the overall mass characteristics of the PCPS and its components—automation elements: electric start-up valve, pressure regulator, evaporator, filling and drainage couplings.

An approach based on the method of combining functions is used to reduce the dimensional and mass characteristics of PCPS elements when forming the PCPS pneumohydraulic scheme for MN. Instead of the pressure regulator and evaporator with HE, the created PCPS demonstration sample includes a small-sized multifunctional flow-through starting chamber, which includes: a cylindrical container with a volume of \( \sim 1 \text{ cm}^3 \), screw-nut type chokes (one or two), and a tubular HE overlay.

To reduce the size of the PCPS as part of the MN, the traditional micro resistojet layout with a coaxial housing arrangement with a self-contained HE and nozzle is replaced with a transverse layout, in which the nozzle axis is perpendicular to the housing axis.

With this approach to the formation of the design image of the PCPS, the following interrelated main design parameters (MDP) can be formed: power consumption of the micro resistojet and HE multifunction flow starting chamber \( N_{\text{mrj}}, N_{\text{HE}} \), maximum thrust of the micro resistojet, pressure and temperature in the micro resistojet chamber before entering the critical section of the nozzle \( P_{\text{mrj}}^{\text{max}}, T_{\text{mrj}}^{\text{max}}, T_{\text{mrj}}^{\text{ch}}, \) the duration of opening the electrovalve \( t_{\text{EV}} \) when PCPS is turned on, the duration of the after-action pulse \( t_{\text{aap}} \), the time to enter the \( t_{\text{mode}} \) mode, as well as average integral characteristics for pressure, temperature, thrust, and specific impulse when the micro resistojet enters the mode \( P_{\text{int}}^{\text{mode}}, T_{\text{int}}^{\text{mode}}, T_{\text{int}}^{\text{spec}}, \) and on the section of the after-action pulse \( P_{\text{int}}^{\text{aap}}, T_{\text{int}}^{\text{aap}}, P_{\text{aap}}^{\text{aap}}, P_{\text{spec}}^{\text{aap}} \), determining the required fuel reserves \( m_t \) for the implementation of a given characteristic speed, the number of inclusions pulse PS \( N \) and the speed increment for a single inclusion pulse PS \( \Delta V_{\text{rad}} \).

The mutual influence of MDP determines the complexity of choosing MDP at the early stages of design when forming the design appearance of PCPS and puts forward the actual task of their experimental study using a demonstration sample of pulsed PCPS.

2. Problem statement

In this paper, the task of experimental studies of a demonstration sample of a small-sized PCPS for MN in a vacuum, developed by the method of combining functions by introducing a combined circuit into a multi-functional flow starting chamber.

The purpose of experimental research: to determine the ways to create a PCPS MN at the early stages of design when forming the design appearance of PCPS.

The main objectives of experimental studies of PCPS when using isobutane as a working medium are:
- confirmation of PCPS operability for MN;
- MDP PCPS research using single and dual throttle pneumohydraulic scheme (PHS);
– determination of the design appearance of the PCPS for MN for further theoretical and experimental studies.

3. Theory
Non-toxic isobutane was selected as the working fluid of the PCPS demonstration sample under the operating safety conditions in preparation for the MN launch.

The following PHS are considered:
– with a single throttle with a pressure sensor at the inlet to the critical section of the micro resistojet nozzle (figure 1a);
– with a single throttle with a temperature sensor at the entrance to the critical section of the micro resistojet nozzle (figure 1b);
– with two chokes with a pressure sensor at the inlet to the critical section of the nozzle (figure 2).

1 – installation for filling the working fluid; 2, 3 – filling and drainage couplings; 4 – fuel tank; 5 – filter; 6 – electrovalve; 7 – adjustable threaded choke; 8 – multi-function flow starting chamber; 9 – micro resistojet; 10 – pressure sensor; 11 – temperature sensor

**Figure 1.** PHS PCPS with a single throttle with a pressure sensor (a) and a temperature sensor (b) at the entrance to the critical section of the micro resistojet nozzle

1 – installation for filling the working fluid; 2, 3 – filling and drainage couplings; 4 – fuel tank; 5 – filter; 6 – electrovalve; 7, 9 – adjustable threaded choke; 8 – multi-function flow starting chamber; 10 – micro resistojet; 11 – pressure sensor

**Figure 2.** PHS PCPS with two chokes with a pressure sensor at the entrance to the critical section of the micro resistojet nozzle
Small-sized adjustable chokes are made according to the screw-nut scheme with the passage of the working fluid through a threaded connection. A cylindrical multi-function flow-through starting chamber with a volume of 1 cm³ is equipped with an overhead external HE with a power of up to 4 W. According to the layout conditions, the PCPS as part of the MN micro resistojet with an autonomous HE is made according to a transverse scheme with the nozzle axis perpendicular to the longitudinal axis of the micro resistojet (figure 3).

![Diagram](image)

1 – nozzle; 2 – housing with gas lines; 3 – working fluid inlet fitting; 4 – autonomous HE; 5 – pressure (temperature) measuring line

**Figure 3.** Basic 3D model (a), 3D model of the heating part (b) and experimental sample (c) micro resistojet transverse scheme

Parameters of the micro resistojet nozzle: the diameter of the critical section of the nozzle is 1 mm, the diameter of the nozzle section is 9 mm. The micro resistojet housing with gas ducts is made using additive technology.

A General view of the PCPS demonstration sample located in the vacuum chamber is shown in figure 4.

![Diagram](image)

1 – PCPS; 2 – micro resistojet; 3 – pressure sensor (when measuring the temperature, a thermocouple is installed); 4 – multi-function flow starting chamber with HE; 5 – pressure (temperature) measuring line; 6 – autonomous HE; 7 – fuel supply line; 8 – vacuum chamber

**Figure 4.** General view of the PCPS demo with micro resistojet transverse scheme

The experiments used a sequential scheme for starting the PCPS with preheating the flow-through starting chamber and the micro resistojet before feeding the working fluid: the design of the micro resistojet was heated with a power of 9 W to a temperature of near 700 °C, and then the working fluid was fed.

The estimation of the realized reserves of the characteristic $\Delta V_{\text{char}}$ speed of PCPS in the MN was made according to the formula [18, 19]:

$$\Delta V_{\text{char}}$$
\[
\Delta V = -g \cdot F_{\text{spec. imp}} \ln \left( \frac{m_{\text{MN}} - P_{\text{spec. imp}} \cdot t_{\text{MN}} N - P_{\text{spec. imp}} \cdot t_{\text{MN}} (N - 1)}{m_{\text{MN}} - P_{\text{spec. imp}} \cdot t_{\text{MN}} N} \right) - g \cdot F_{\text{spec. imp}} \ln \left( \frac{m_{\text{MN}} - P_{\text{spec. imp}} \cdot t_{\text{MN}} N - P_{\text{spec. imp}} \cdot t_{\text{MN}} (N - 1)}{m_{\text{MN}} - P_{\text{spec. imp}} \cdot t_{\text{MN}} N} \right).
\]

where \( \Delta V \) is the characteristic velocity realized by the PCPS as part of the MN; \( P_{\text{spec. imp}} \) – the average specific impulse of the micro resistojet at the pressure drop section (aftereffect pulse after closing the valve); \( t_{\text{MN}} \) – micro resistojet thrust in the area of pressure increase; \( P_{\text{int}} \) – micro resistojet thrust in the pressure drop area; \( t_{\text{mode}} \) – operating time of the micro resistojet when entering the mode with the valve open.

PCPS characteristics were evaluated using parametric dependencies for calculating micro resistojet thrust and specific impulse through gas dynamic functions of the gas flow [14-17]:

\[
P_{\text{int}} = p_n \cdot F_n \cdot K_t;
\]

\[
K_t = \left( \lambda_s + \frac{1}{\lambda_s} \right) \left( \frac{2}{k+1} \right);
\]

\[
P_{\text{spec. imp}} = a_{\text{ct}} \cdot K_{\text{ad}};
\]

\[
a_{\text{ct}} = W_{\text{ct}} = \sqrt{\frac{2k}{k+1}} \frac{R T_n}{M_g};
\]

\[
K_{\text{ad}} = \left( \lambda_s + \frac{1}{\lambda_s} \right) \left( \frac{k+1}{2k} \right);
\]

\[
q(\lambda_s) = \frac{F_a}{F_n} = \frac{W_n \rho_n}{W_{\text{ct}} \rho_{\text{ct}}} = \lambda_s \left( \frac{k+1}{2} \right) \left( 1 - \frac{k-1}{k+1} \lambda_s^2 \right)^{(k-1)};
\]

\[
\tau(\lambda_s) = \frac{T_n}{T_{\text{ct}}} = \left( 1 - \frac{k-1}{k+1} \lambda_s^2 \right);
\]

\[
\pi(\lambda_s) = \frac{p_{\text{int}}}{p_{\text{ct}}} = \left( 1 - \frac{k-1}{k+1} \lambda_s^2 \right)^{(k-1)};
\]

\[
\epsilon(\lambda_s) = \frac{p_{\text{int}}}{\tau(\lambda_s)} = \left( 1 - \frac{k-1}{k+1} \lambda_s^2 \right)^{(k-1)};
\]

where \( K_t \) – dimensionless thrust coefficient; \( K_{\text{ad}} \) – dimensionless coefficient of specific impulse; \( T_n, T_{\text{ct}} \) – gas temperature at the nozzle section and in the micro resistojet chamber, respectively; \( \rho_n, \rho_{\text{ct}}, \rho_{\text{ct}} \) – gas density at the nozzle section, in the micro resistojet chamber, and in the critical section of the nozzle, respectively; \( p_n, p_{\text{ct}}, p_{\text{ct}} \) – gas pressure at the nozzle section and in the micro resistojet chamber, respectively; \( F_n, F_{\text{ct}} \) – the area of the nozzle cut-off and the critical section of the nozzle, respectively; \( W_n \) – gas flow rate at the nozzle cross-section; \( a_{\text{ct}} = W_{\text{ct}} \) – gas flow velocity equal to the speed of sound in the critical section of the nozzle; \( k \) – the impact adiabatic index of the gas used; \( R \) – universal gas constant; \( M_g \) – molar mass of the gas used; \( q(\lambda_s) \) – relative area of the critical section of the nozzle; \( \tau(\lambda_s) \) – relative temperature at the nozzle cross-section; \( \pi(\lambda_s) \) – relative pressure at the
nozzle cross-section; \( \varepsilon(\lambda_c) \) – relative density at the nozzle cross-section; \( \lambda_c = W_n/\alpha_{cr} \) – relative velocity of gas flow at the nozzle section.

4. Experimental results
During the research, the problems of determining the characteristics of the PCPS demo sample for MN with different PHS were solved.

The results of the experiments are presented as graphs:

– changing the pressure in the micro resistojet chamber from time to time for PHS PCS with a single throttle (throttle setting option 1): power of HE micro resistojet \( N_{\text{mrj}} = 9 \) W, power of HE capacity not \( N_{\text{HE}} = 4 \) W, duration of opening the electrovalve \( t_{EV} = 0.25 \) s, the maximum pressure in the micro resistojet chamber with the valve open was \( p_{\text{mrj,ch}}^{\text{max}} = 0,102 \) MPa, the duration of the aftereffect pulse is \( t_{\text{aap}} = 0.54 \) s, average integral pressure in the aftereffect pulse section \( p_{\text{aap}}^{\text{int}} = 0,0365 \) MPa, the average integral pressure when entering the mode with the electric valve open \( p_{\text{int}}^{\text{mode}} = 0,0696 \) MPa (figure 5);

– changing the temperature at the micro resistojet nozzle cross section from time to time for PHS PCS with a single throttle (throttle setting option 1): the maximum temperature at the nozzle section was \( T_{\text{mrj,n}}^{\text{max}} = 325.6 \) K with the power supplied to the HE micro resistojet \( N_{\text{mrj}} = 9 \) W and the power of the ne multi-function flow starting chamber \( N_{\text{HE}} = 4 \) W, average integral temperature at the nozzle cross section in the aftereffect pulse section \( T_{\text{int,n}}^{\text{aap}} = 325.2 \) K, average integral temperature at the nozzle section when entering the mode with the electric valve open \( T_{\text{int,n}}^{\text{mode}} = 323.5 \) K, micro resistojet warm-up time before opening the tetmd valve \( t_{\text{mrj}} = 16 \) minutes (figure 6);

– changing the pressure in the micro resistojet chamber from time to time for PHS PCS with a single throttle (throttle setting option 2): \( N_{\text{mrj}} = 9 \) W, \( N_{\text{HE}} = 4 \) W, \( t_{EV} = 0.25 \) s, \( p_{\text{mrj,ch}}^{\text{max}} = 0,095 \) MPa, \( t_{\text{aap}} = 0.48 \) s, \( p_{\text{aap}}^{\text{int}} = 0,0418 \) MPa, \( p_{\text{int}}^{\text{mode}} = 0,0592 \) MPa (figure 7);

– changing the temperature at the micro resistojet nozzle cross section from time to time for PHS PCS with a single throttle (throttle setting option 2): the maximum temperature in the chamber micro resistojet \( T_{\text{mrj,ch}}^{\max} = 404 \) K, \( N_{\text{mrj}} = 9 \) W, \( N_{\text{HE}} = 4 \) W, average integral temperature in the chamber micro resistojet on the section of the aftereffect pulse \( T_{\text{int}}^{\text{aap}} = 403.3 \) K, average integral temperature in the micro resistojet chamber when entering the mode with the valve open \( T_{\text{int}}^{\text{mode}} = 396.9 \) K, \( t_{\text{mrj}} = 11 \) minutes (figure 8);

– changing the pressure in the micro resistojet chamber from time to time for PHS PCS with two throttles (setting the throttles option 3): \( N_{\text{mrj}} = 9 \) W, \( N_{\text{HE}} = 4 \) W, \( t_{EV} = 0.25 \) s, \( p_{\text{mrj,ch}}^{\text{max}} = 0,0270 \) MPa, \( t_{\text{aap}} = 3.6 \) s, \( p_{\text{aap}}^{\text{int}} = 0,0112 \) MPa, \( p_{\text{int}}^{\text{mode}} = 0,0132 \) MPa (figure 9);

– changing the temperature in the micro resistojet chamber from time to time for the PHS PCPS with two throttles (setting the throttles option 3): \( N_{\text{mrj}} = 9 \) W, \( N_{\text{HE}} = 4 \) W, \( t_{EV} = 0.25 \) s, \( T_{\text{mrj,ch}}^{\max} = 440.5 \) K, \( T_{\text{int}}^{\text{aap}} = 438.1 \) K, \( T_{\text{int}}^{\text{mode}} = 438.8 \) K, \( t_{\text{mrj}} = 11 \) minutes (figure 10).
Figure 5. Changing the pressure in the micro resistojet chamber from time to time for a single-throttle PHS PCPS (option 1)

Figure 6. Temperature change at the micro resistojet nozzle cross section from time to time for PHS PCPS with one throttle (option 1)

Figure 7. Changing the pressure in the micro resistojet chamber from time to time for a single-throttle PHS PCPS (option 1)
5. Discussion of results
The results of experiments and numerical studies for variants 2, 3 are shown in table 1.
The results of experimental and numerical studies have shown:

- PCPS with a multi-function flow starting chamber, with the ability to install both one and two throttles, allows you to get different values of the maximum thrust of the micro resistojet;

- in the pressure range $p_{\text{int}}^\text{max} = (0.065-0.095)$ MPa, the maximum thrust of the PCPS with one throttle meets the requirements: $p_{\text{int}}^\text{max} = (108-159)$ mN;

- at pressures $p_{\text{int}}^\text{max} < 0.065$ MPa, the maximum thrust of an PCPS with one or two throttles decreases: $p_{\text{int}}^\text{max} < 100$ mN; so, at a pressure $p_{\text{int}}^\text{max} = 0.027$ MPa, the maximum thrust value $p_{\text{int}}^\text{max} = 45$ mN;

- when the volume of the multi-functional flow starting chamber is ~ 1 cm³ and the duration of the electric valve is 0.25 s, the pressure $p_{\text{int}}^\text{max}$ change is achieved by adjusting the throttle (s);

- fuel reserves to reach $V_{\text{char}} = 100$ m/s are determined by the heating temperature of the gaseous fuel for the available power of the HE micro resistojet 9 W;

- when the power consumption of the overhead tubular HE of the multi-function flow-through starting chamber is limited to 4 W, which are not directly in contact with the fuel, the fuel is in a gaseous state, but the preheating temperature of the fuel is limited;

- to increase the degree of heating of gaseous fuel, a multifunctional flow-through starting chamber with an internal location of the ne that is directly in contact with the fuel is necessary;

- when the fuel is heated to ~ $T_{\text{int}}^\text{mode} = 573$ K, the fuel reserves will be reduced from $m_{\text{T}} = 0.79$ kg to $m_{\text{T}} \sim 0.7$ kg;

- a significant number of switching on of the PCPS (for $B_2 N = 11914$) sets the task of ensuring the reliability of operation by reserving the HE micro resistojet;

- PCPS provides sequential connection of energy-consuming elements (electric valve, HE multifunctional flow starting chamber, HE micro resistojet) and the ability to redistribute electrical power between them; this allows you to use an electric valve with significant energy consumption within the allocated power on the PCPS.

Based on the results of experimental and numerical studies, a 3D model of an advanced PCPS with a multifunctional flow-through starting chamber and a redundant cross-section miro resistojet has been developed that meets the requirements for the size of the format up to 2U (figure 11 – 13).
1 – fuel tank; 2 – reserved micro resistojet; 3 – pressure sensor; 4 – multifunction flow-through starting chamber with combined circuit and functions: vessel+HE+ adjustable threaded choke; 5 – electrovalve; 6 – drainage coupling; 7 – filling coupling

Figure 11. 3D model of PCPS with redundant micro resistojet and multi-function flow starting chamber of combined circuit

1 – throttle part HE; 2 – multi-function flow starting chamber; 3 – pressure sensor; 4 – HE

Figure 12. 3D model of a multi-function flow starting chamber combined with the following functions: capacity+NOT+adjustable threaded choke

1 – nozzle; 2 – housing micro resistojet; 3 – reserved HE; 4 – working fluid inlet fitting; 5 – gas pipelines

Figure 13. Micro resistojet cross-section scheme with redundancy HE

6. Conclusion

1. Based on the results of experimental and numerical studies, the performance of the PCPS demonstration sample with a multifunctional flow-through starting chamber and a micro resistojet cross-section scheme was confirmed.

2. The PCPS with a multi-function single-throttle flow-through starting chamber provides the micro resistojets set thrust of 159 mN.

3. The set speed increment MN when PCPS is switched on once $\Delta V = \Delta V_{\text{set}} \leq 0.01$ m/s for PCPS with a single throttle is provided by optimizing the volume of the multi-function flow starting chamber, the
duration of opening the electric valve, the throttle parameters and HE of the storage tank and micro resistojet.

4. For further experimental and theoretical research, a 3D model of an advanced PCPS with a multifunction flow-through starting chamber and a redundant micro resistojet cross-section scheme has been developed that meets the requirements for the dimensions of MN. Main features of the PCPS:
   – multifunctional flow starting chamber is based on a vaporizer with an autonomous HE;
   – threaded choke is made using an autonomous HE housing;
   – micro-resistor is made with reserved HE.

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