Smallsat’s dilatometric micromotor: estimation of characteristics

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Abstract. The article reflects some results of the work of the authors on the creation of reactive corrective micro-motors for spacecraft of nanoglass. A special feature of these micro-motors is the use of a dilatometric element as a shut-off actuator, which is a working gas heater. A prototype of a dilatometric micro-motor was developed and manufactured, on which, under vacuum conditions, efficiency studies were carried out and the output thermodynamic parameters of the gas were obtained. Dilatometric valve engine used thus reducing the nitrogen pressure of 2.8 bar and up to 120 Pa was carried out by the gas flow rate $1.8 \times 10^{-6}$ kg/s and heated to a temperature of 470 K. the Specific impulse thrust was 630-650 m/s. Power was 2.6 watts.

1. Introduction
Ultra-small spacecraft (USSC) are used as a means of solving problems in the fields of space research because they can test spacecraft for human safety in an economic way. The USSC class of devices are those weighing up to 100kg (micro-, nano-, pico- and femto satellites). This class of devices has been made possible by the development and wide distribution of microelectronics, which has been implemented in the miniaturization of the payload and control systems. And the reduction in the cost of USSC components has expanded research in this area to include higher education institutions all over the world, where their development is carried out by undergraduate students and post-graduate students.

The launching of USSC’s is carried out by a passing method or by astronauts while in space when they leave their spacecraft (ISS).

The niche of cheap modular USSC is constantly expanding. This is especially noticeable by the increasing frequency of launches of satellites into a near-earth orbit. For example, on 14 July, 2017, Soyuz-2.1a led the launching of 72 small satellites with the launching of the spacecraft “Canopus-V-IR” and in India, with a record number of 104 satellites led by the rocket PSLV-C37.

The next step of development of the USSC class will be the development of guided flights.

For use in large spacecraft, USSC introduce a reactive propulsion system that ensures the correction of the satellite’s orbit, the development of apparatus along the orbits of operation in the case of group excavations, and the disposal of the USSC after the end of its active operation period and interplanetary flights.

Unlike microelectronics, the engine building area for USSC is not developing so quickly. The most significant limitation is the amount of excess capacity that the USSC has. The miniaturization of the electronic components of the USSC leads to a reduction in the mass and dimensions of the apparatus and a reduction in the power consumption. The useful surface area of the solar panels is limited by the dimensions of the apparatus. As a consequence, the excess power falls linearly with a decrease in the mass of the apparatus. For example, on the USSC of the CubeSat formfactor of the base standard 1U,
the excess power is not more than 1W, while the electromagnetic shut-off valve, mandatory for traditional reactive low-thrust systems, according to some manufacturers, consumes not less than 1W of energy. Because of this, the most common propulsion systems (PS) use "cold gas". Such systems have a flight operation history which has demonstrated that they are easy to implement and reliable, because there are no high temperatures. But a significant disadvantage of PS on "cold gas" is their low profitability.

Another significant disadvantage of remote control on "cold gas" is their low efficiency and high thrust values. The higher thrust has a negative effect on the craft’s orientation and stabilization because of the USSC’s small mass. For example, the low-thrust engine of the MicroThruster designed by the Marotta engineering company for the ST-5 (25 kg) has a specific impulse of thrust of 65 s for nitrogen operation, a pull of 0.05-2.36 N (depending on the pulse width), and consumes 1 Watt in the pulsed mode [1]. This device is a high-speed impulse valve with pulse duration up to 5 ms. The thrust value is set by the opening time of the flow section. It should be noted that the USSC form factor CubeSat 1U has a mass of up to 1 kg. An interesting device is the correction MEMS company NanoSpace, the working body of which is selected butane. The specific impulse of the motor is 50-75 s, the power consumption is 2Watt at a thrust of 0.01-1 mN [1]. Another micromotor with flight tests is the CNAPS of the Canadian company UTIAS / SFL, operating on sulfur hexafluoride and creating a thrust of 12.5-40 mN at a specific impulse of 40 s.

In PS USSC, resistive micro-motors (electrothermal micromotors) have found application, where the working medium is subjected to preliminary heating, which provides an increase in the specific impulse of thrust. One example is the MRJ Thruster [2] (company Busek) with an energy consumption of 3-15 W, a specific impulse of thrust of 80-150 s and thrust of 2-10 mN. Working body MRJ Thruster-ammonia. Also, it is possible to single out the engine PUC (Propulsion Unit for Cubesats) which is produced by CU Aerospace and VACCO [3], which powers up to 15 W, thrust pulse 70 s and thrust 0.45 N.

The typical scheme of the correcting propulsion system (CPS) USSC is a sequential chain of elements: the fuel tank in the working body - the shut-off electrovalve - the heater of the working body (for resistive motors) - pressure reducer – and the electrothermal micro motor (ETMM). This scheme is used for SSC with a mass of 10 kg with an excess of electrical power from 30 to 110W. The USSC format begins with apparatuses weighing less than 10kg. The traditional layout scheme allows a CPS to operate mainly on "cold gas", i.e. without heating the working fluid.

Structurally, CPS SSC is a sequence of nodes, each of which has a single task. The unavoidable irreversible heat losses in each element reduce the electrical efficiency of the CPS.

Minimization of losses and miniaturization of CPS elements by direct scaling of the elements' constructions does not justify itself, because the boundary conditions for ensuring the operability of electromagnetic and heat-producing devices often conflict with each other. Also, with direct scaling of the construction, consumed powers collide with unscaled gas-dynamic processes occurring in the CPS tract.

From what has been stated above, it follows that at present, there is a problem of developing energy-efficient CPS of the USSC, which ensure the preservation of the given high output characteristics of the ETMM.

The authors proposed the concept of a micromotor, which makes it possible to combine a throttling valve and a working body heater in one technical node; the "Swiss knife" concept. The basis of the mechanics of the valve drive is the dilatometric effect, which is unavoidable in the use of electric heating elements. This approach does not exert an additional energy load on the power supply systems of the USSC. Thus, the increase in the energy efficiency of the CPS of the USSC is made through the intensification of energy exchange processes due to the reduction in the number of intermediate links of the KDU and the use of dissipative energy, using dilatometric effects.

2. Formulation of the problem

The work is based on the results of the experiments carried out with subsequent theoretical processing on the basis of the known laws of physics.

The following tasks have been posed by the authors:
1. Development and creation of a prototype of an electrothermal micromotor with dilatometric drive of a shut-off throttling valve;
2. Thermal experimental studies of the prototype under vacuum with nitrogen as a working fluid;
3. Theoretical processing of the results of experimental prototype research.

3. Theory
An experimental sample of a dilatometric micromotor (DMM) is shown on Figure 1. The throttling valve 1 is made in the form of a cylindrical sleeve with seals made of vacuum rubber and a side fitting 5 for insertion of the working fluid. The valve has the ability to adjust the flow rate with a screw. This is necessary to adjust to the conditions of the vacuum chamber. The dilatometric element 2 is made in the form of a resistance of the rod, heated by a graphite element, with a diameter of 2 mm. At the end of element 2 is the valve needle. In Figure 1 dilatometric element is shown separately, prior to assembly. The gas path in the engine is an annular channel formed by the element 2 and the motor casing 3. On the tap 4, the heated working medium enters the T-piece, where it enters the rotameter at the fitting 7. The fitting 6 is for connection of a manometer.

![Figure 1. Experimental sample of a micromotor with dilatometric valve drive](image)

The engine elements are made of AISI 321 steel. The fixation and sealing of the elements is with an epoxy resin.
The operation of the DMM is carried out as follows: When the electric current is applied to the element 2, it heats up, the material undergoes a linear expansion, the position of the needle in the valve 1 changes, and the working medium enters the annular gap between the elements 2 and 3, where it heats and expels through the side branch 4. Thus, reactive thrust is created.

Figure 2 shows the experimental setup. In the figure, the items are: 1-vacuum chamber; 2-investigated DMM sample; 3-thermoelectric converters installed on the body and at the side branch of the DMM; 4-rotameter PM-A-0.063 GUZ; 5-rotameter PM-A-0.1 GUZ; 6-manometer in the mains; 7-gallon with nitrogen; 8-gas reducer; 9-Vacuum plate-rotor pump NVR-16D; 10-control panel of the vacuum chamber; 11-lamp PMT-6-3M; 12-multichannel precision temperature meter MIT-8; 13-PC; 14-a vacuum gauge Meradat-VIT 16T3 / 2P / 485 / 2M; 15-valve electromagnetic shutoff; 16-manometer at the exit from the DMM.

In the course of the experiment, the following values were set: the inlet pressure in the DMM was 2.8 atm. (according to the pressure gauge item 6 in Figure 2) and the electrical voltage on the dilatometer element 3 V (power consumption 2.6 W).

Measured and recorded values in the experiment were: indications of rotameters RM-A-0.063 GUZ and RM-A-0.1 GUZ; temperature of the hull elements of DMM, recorded by thermocouples (item 3, Figure 2); the gauge reading (item 16, Figure 2); The readings of the Meradat-VIT 16T3 / 2P / 485 / 2M vacuum gauge (item 14, Figure 2).

In the course of experimental studies, at the first stage, the fact of DMM operability in vacuum conditions was confirmed: after 25-30 seconds, after applying thermal power to the dilatometric
element, the float of the rotameter installed in the vacuum chamber came into motion. The initial temperature of the dilatometer element was 18°C.

Figure 2. Experimental setup for determining the DMM parameters

To determine the mass flow rate of gas in a high-pressure pipeline, a rotameter was installed (item 4, Figure 2), however, the sensitivity of the instrument was not sufficient, the float of the rotameter 4 did not come into motion with a fluctuating float of the rotameter 5. Thus, the mass flow was determined for the pressure increase in the vacuum chamber (item 1, Figure 2) with the pump off (item 9, Figure 2), the pressure change was recorded with a vacuum gauge 14. With the known volume of the vacuum chamber, the mass flow through the flowing part of the DMM is \( m = 1.8 \times 10^{-6} \) kg/s.

At the second stage of the study, the thermodynamic parameters of the gas in the DMM were determined. An important parameter is the temperature of nitrogen. It was determined in three ways: on the basis of the readings of a rotameter installed in a vacuum chamber; on the basis of the drop in the temperature of the DMM body during the passage of nitrogen; based on the equation of the gas temperature in the heated pipeline, derived from the Newton-Richman equations and the total gas energy.

1. Determination of gas parameters through indications of a rotameter.

The technique is based on two basic equations: the float equation for a rotameter [4] and the van der Waals equation for a real gas.

The equilibrium equation of a float in a rotameter has the form:

\[
m_p g = C_X \frac{\rho_N^e \pi^2}{2} F_p + \rho_N^e V_p,
\]

where \( m_p = 0.36 \) grams - the mass of the float of the rotameter (the value is given for the PM-A-0.1 GUZ device, float material D1T); \( C_X \) – coefficient of aerodynamic drag of the float; \( \rho_N^e \) - density of nitrogen in a rotametric tube; \( F_p, V_p \) – the area of the midsection and the volume of the float, respectively. The largest diameter of the float of the PM-A-0.1 GUZ device is \( d_f = 6 \) mm.

In the tests, the float of the rotameter installed in the vacuum chamber was not in equilibrium in the rotametric tube, but fluctuated, assuming a position from touching the lower stop to 56 divisions on the scale of the rotameter.

The moment of detachment of the float from the lower stop was considered. The diameter of the pipeline (nominal diameter) of the rotameter is \( d_t = 3 \) mm, hence the flow rate flowing onto the cone of the float can be found from the expression:

\[
u = \frac{4m}{\pi d_t^2 \rho_N^e}.
\]

Here \( \rho_N^e \) – is the unknown nitrogen density at the entrance to the rotameter.

The coefficient of aerodynamic drag of the float was determined by the method of [4]. The final formula for deriving the drag coefficient can be written as:
Substituting equations (2) and (3) into equation (1), we obtain the value of the nitrogen density at the input to the rotameter $\rho_{N_2} = 9.25 \times 10^{-4} \text{ kg/m}^3$.

The coefficient of aerodynamic resistance is equal to $C_x = 0.477$, it agrees with the experimental data on flow past cones [5]. For example, for a cone with an angle of 30° $C_x = 0.35$, for an angle of 60° $C_x = 0.61$. The cone angle of the float rotameter RM-A-0.1 GUS is 45°.

The nitrogen temperature at the outlet from the DMM can be determined from the Van der Waals equation:

$$P_{N_2} + \frac{a_{N_2} \rho_{N_2} R}{M_{N_2}} \left( \frac{M_{N_2}}{\rho_{N_2} R} - b_{N_2} \right) = T_1 R,$$

where $P_{N_2} = \frac{4 m_g}{\pi d_p^2} = 124,905 \text{ Pa} – \text{minimum float detachment pressure from the stop (pressure in the DMM tract)}; a_{N_2}, b_{N_2} – \text{Van der Waals constants for nitrogen; } M_{N_2} – \text{is the molecular weight of nitrogen; } T_1 – \text{is the unknown temperature of nitrogen; } R – \text{is the universal gas constant.}$

2. Determination of gas parameters through the drop in the temperature of the hull elements of the DMM.

The methodology is based on the equation of the balance of the input and output power and the estimation of the gas temperature from the temperature difference between the hull and the gas supply and with the gas fed along the path.

The initial data in this method are the geometric dimensions of the flow section, the physical properties of the materials, the thermocouple readings, the mass of the hull elements.

Thermal loading of DMM occurred under conditions of a vacuum chamber for 5000 s. During this time, the modes of operation of the DMM changed (Figure 3):

A – mode of heating with nitrogen supply (solenoid valve item 15 on Figure 2 is open);

B – mode of gas supply without heating;

C – mode of heating without supply of nitrogen to the pipeline (solenoid valve item 15 on Figure 2 is closed);

D – heating mode with nitrogen supply (solenoid valve item 15 on Figure 2 is open);

E – is the cooling regime with nitrogen supply (there is no heating of the dilatometric element).

![Figure 3. The results of the thermocouple readings mounted on the DMM body (№ 1), at the lateral branch (№ 2), and the cold junction (№ 3)](image-url)
For the analysis of the thermal regime, mode D was selected (Figure 3), when nitrogen enters the heated DMM path. It can be seen that the transient mode of changing the internal energy of the DMM body material takes 440 s. During this time, the temperature drops by 3.5 K. Curve № 2 shows that in the same section, the temperature changes by the same amount. Hence, it can be assumed that the entire DMM construction, when cooled with nitrogen, loses 3.5–4 K. The mass of DMM elements participating in the heat exchange is 22 grams (as measured directly by electronic scales).

Thus, the thermal power received by nitrogen when it passes through DMM can be expressed:

$$N_{N_2} = \sum_{i=1}^{n} c_{pi} m_i \Delta T_i,$$  

(5)

where $c_{pi}$ - the specific heat of the i-th substance, which is part of the DMM; $m_i$ - mass of the i-th substance, which is part of the DMM; $n$ - is the number of DMM constituents involved in heat transfer and heat transfer; $\Delta T_i$ is the temperature drop across the DMM case; $t$ - is the time of the transient process. Because all DMM components involved in heat transfer are made of AISI 321 steel, then in (5) the specific heat of this steel and the weight of 22 grams are taken.

From the power balance equation, it is necessary to determine the temperature of the dilatometric element, since there was no physical possibility to bring thermoelectric converters to it. In the steady state, in the absence of nitrogen, the electrical power supplied to the dilatometric element is expended on heating by the radiation of the inner surface of the DMM body and on the radiation of the body into the surrounding space:

$$N = \sigma \left[ \left( T_d^4 - T_k^4 \right) \varepsilon_k \cdot F_1 + T_k^4 \varepsilon_F \sum_{i=1}^{n} \pi D_i \right].$$  

(6)

where $\varepsilon_k = \frac{1}{\varepsilon} \left( \frac{F_1}{F_2} \cdot \frac{1}{\varepsilon_k} - 1 \right)$ - is the decreased degree of blackness of the system of bodies from the dilatometric element located inside the shell; $\varepsilon = 0.95$ – the degree of blackness of the surface of AISI 321 steel [6]; $\sigma$ – the Stefan-Boltzmann constant; $T_k$ – is the unknown temperature of the dilatometric element; $T_k = 356$ K – is the maximum equilibrium temperature of the DMM body when heated without gas; $N = 2.61$ W – electric power input. The surface area of the dilatometric element $F_1$, the inner surface of the housing $F_2$ and the outer surface of the housing $F_3$ are determined by measuring the linear and diametric dimensions of the elements.

To determine the temperature of nitrogen in the annular space of the DMM tract, the Newton-Richman formula [7] is applied:

$$N_{N_2} = \alpha (T_d - T_{N_2}) \pi D_k L_k.$$  

(7)

In formula (7), the heat transfer coefficient is determined in terms of the Nusselt number:

$$\alpha = \frac{Nu_{N_2} \lambda_{N_2}}{L_k},$$  

(8)

where $\lambda_{N_2}$ – coefficient of thermal conductivity of nitrogen at thermodynamic parameters of gas in the gap; $L_k$ – the length of the annular gap; $D_k$ – equivalent diameter of the annular gap.

It is assumed that the flow regime of the rarefied gas in the gap is laminar. The average heat transfer coefficient for a laminar flow of gas in a pipe under conditions $L_k / D_k > 10$ and Re > 10 can be determined from the formula [7]:

$$Nu = 1.4 \left( \frac{Re D_k}{L_k} \right)^{0.4} \left( \frac{Pr_{N_2}}{Pr_k} \right)^{0.33} \left( \frac{Pr_{N_2}}{Pr_k} \right)^{0.25},$$  

(9)

where $Pr_{N_2} = \frac{\eta_{N_2} C_p}{\lambda_{N_2}}$ – Prandtl number according to the gas temperature at the outlet of the valve when entering the gap; $Pr_k = \frac{\eta_{k} C_p}{\lambda_{k}}$ – the Prandtl number at the internal wall temperature of the gap.
The isobaric heat capacity of nitrogen, with thermodynamic parameters in the gap, can be expressed as the heat capacity of an ideal diatomic gas:

\[ C_p = \frac{7R 10^3}{2M_{N_2}}, \]  

(10)

where \( R \) – is the universal gas constant; \( M_{N_2} \) – is the molar mass of nitrogen, \( \text{kg/kmol} \).

Reynolds number in the annular gap:

\[ \text{Re} = \frac{4\eta h}{\pi D_\text{z} \eta_{N_2} \rho_{N_2}^R}, \]  

(11)

where \( \eta_{N_2} \) – is dynamic viscosity of nitrogen in the gas duct.

The dynamic viscosity of a rarefied polyatomic gas can be found as a function of the empirical parameters [8]:

\[ \eta_{N_2} = 2.6693 \times 10^{-6} \sqrt{M_{N_2} T \sigma^2 \Omega_\eta}, \]  

(12)

where \( M_{N_2} \) – is the molecular weight of nitrogen; \( T \) – is the temperature in \( \text{K} \); \( \sigma \) – is the diameter of the molecules in \( \text{Å} \); \( \Omega_\eta \) – is the slowly varying function of the dimensionless temperature. The last two quantities are tabular and are given in [8]. Dynamic viscosity is determined for the initial temperature and temperature of the housing.

The thermal conductivity of rarefied nitrogen can be estimated using the dependence [8]:

\[ \lambda_{N_2} = 0.083 \frac{M_{N_2}^2 T \sigma \Omega_k}{\rho \sigma^2 \Omega_\eta}, \]  

(13)

where \( \Omega_k \) – is integral, the numerical value of which is calculated in the framework of the Lennard-Jones intermolecular interaction potential model [8].

Solving equations (7) – (13) one can obtain the required gas temperature \( T_{N_2} \). The temperature value is given in Table 1.

3. Determination of gas parameters is based on the gas temperature equation. This equation is derived on the basis of the equations for the change in the total energy and the Newton-Richmann equation and is written taking into account the small difference in the gas pressures before and after heating:

\[ c_v T_0 = \frac{21,939 \times 10^{-3} M_{N_2}^{0.6} (c_v + R)^{0.33} T_{0,4}^{0.4}}{m^{0.6} \sigma^2 \Omega_6^{0.6} (\rho_{N_2}^R)^{0.4}} \cdot \frac{T_{k,0.4}}{D_k^{0.4}}. \]  

\[ T_{k,0.4} = c_v \left( \frac{21,939 \times 10^{-3} M_{N_2}^{0.3} (c_v + R)^{0.33} T_{k,0.4}^{0.4}}{m^{0.6} \sigma^2 \Omega_6^{0.6} (\rho_{N_2}^R)^{0.4}} \cdot \frac{T_{0,4}}{D_k^{0.4}} \right). \]  

(14)

The initial data for equation (14) are the same as for equations (6) and (7). In (14), the molar heat capacity of a gas at a constant volume is defined as \( c_v = \frac{i}{2} R \), where \( i \) – is the number of degrees of freedom of a nitrogen molecule.

To estimate the velocity of the nitrogen molecules at the exit from the channel, one can use the equation of the average kinetic energy of the molecules for a monatomic gas. This dependence has good convergence with the experimental data for diatomic gases:

\[ v = \sqrt{\frac{3RT_{N_2}}{M_{N_2}}}. \]  

(15)

The possible thrust is determined by the product of the mass flow rate for the gas velocity. The results of the calculation are given in Table 1.
4. Research Results
The results of experimental studies are reflected in Table 1.

| № | Source data | Intermediate value | Parameters DMM |
|---|-------------|---------------------|----------------|
| 1 | The mass of the float of the rotameter \( m_p = 0.36 \) gr. | Aerodynamic drag coefficient \( C_x = 0.477 \) | Gas temperature |
|   | Diameter of the midsection of the float \( d_p = 6 \) mm | The pressure in the tract DMM \( p_d = 124.905 \) Pa | Specific impulse |
|   | The volume of the float \( V_p = 130 \) mm\(^3\) | The density of nitrogen in the tract DMM \( \rho_{N_2} = 9.25 \cdot 10^{-4} \) kg/m\(^3\) | 636.485 m/s |
|   | The oscillation amplitude of the float \( h = 2.5-40 \) mm | | |
|   | Nominal diameter of the flowmeter \( d_r = 3 \) mm | | |
|   | Taper rotometrics tube 1/200 | | |
|   | Mass flow of nitrogen \( \dot{m} = 1.8 \cdot 10^{-6} \) kg/s. | | |

2. The maximum equilibrium surface temperature during heating without gas 356 K
The maximum equilibrium surface temperature when heating with gas 352.5 K (area D, pic. 3)
During the transition process \( t = 440 \) s.
Weight DMD \( m = 22 \) gr.
The input electrical power \( N = 2.61 \) W
| | | | |
|---|----------------|------------------|
|   | Dilatometric element temperature \( T_c = 449.35 \) K | Gas temperature | 477.44 K |
|   | Power, adopted by the gas \( N_{K_2} = 0.096 \) W | Specific impulse | 651.9 m/s |
|   | Dynamic viscosity \( \eta_{N_2} = 1.74 \cdot 10^{-5} \) Pa·s and \( \eta_{N_2} = 2.375 \cdot 10^{-5} \) Pa·s | | |
|   | Thermal conductivity \( \lambda_{N_2} = 0.019 \) W/(K·m) | Thrust | 1.19 mN |
|   | Heat transfer coefficient \( \alpha = 4.543 \) W/(m\(^2\)·K) | | |

Mass flow of nitrogen \( \dot{m} = 1.8 \cdot 10^{-6} \) kg/s
Geometric characteristics of the flow part

3. Dilatometric element temperature \( T_c = 449.35 \) K
Density of nitrogen in the tract DMM \( \rho_{N_2} = 9.25 \cdot 10^{-4} \) kg/m\(^3\)
| | | | |
|---|----------------|------------------|
|   | Gas temperature | 553.648 K | |
|   | Specific impulse | 702 m/s | |
|   | Thrust | 1.28 mN | |

5. Discussion of results
During the work, a prototype of an electrothermal micromotor with a dilatometric drive of a shut-off valve was built. Experimental research has shown, first of all, that the device operates. It was shown that the gas supply starts in 25-30 seconds after the electric power is applied to the dilatometric element and the gas is cut off after 10-15 s after turning off the power. DMM showed good economy, because it creates a specific thrust impulse of the order of 63-70 s at an energy consumption of 2.61 watts. The heat exchange in this DMM is not effective, because 0.096 W was needed to heat the gas. However, the formula (14) and previous experimental studies of the authors show a strong dependence of the heat transfer rate on the conditional passage diameter of the channel. The study showed that, with a low heat transfer efficiency, the DMM output characteristics slightly exceed the output characteristics of the remote control on «cold gas».
The output characteristics of DMM were obtained by three methods, two of which are based on experimental data, formula (14) gives the ultimate thermal capacity of the gas under the selected conditions.
6. Summary and conclusions
A prototype of an electrothermal micromotor for USSC, in which the dilatometric pair performs the functions of a gas reducer, a heater of the working fluid and a locking organ, cuts off the supply of the working substance to the engine path. A new concept of remote control design for USSC is presented, with low energy consumption while maintaining functioning. The working capacity of the device is shown. The performance of the prototype dilatometric valve when opened is 25-30 seconds, when cut-off-10-15 seconds. Specific impulse thrust power 2.61 W, made up 63 to 70 seconds. These values put the studied prototype of DMM in series with the energy-efficient do the «cold gas» [1, 2, 3].

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References
[1] State of the Art of Small Spacecraft Technology URL: https://sst-soa.arc.nasa.gov
[2] Williams D 2012 Propulsion Solutions for CubeSats and Applications URL: http://mstl.atl.calpoly.edu/~workshop/archive/2012/Summer/Day%202/1545-Williams-PropulsionSolutions.pdf (Date of access: 30.10.2017)
[3] Propulsion Unit for CubeSats URL: http://www.vacco.com/images/uploads/pdfs/11044000-01_PUC.pdf (Date of access: 30.10.2017)
[4] MI 1420-86 guidelines. GSE. Flowmeters of constant pressure drop. The conversion of metrological characteristics.
[5] Idelchik I E 1992 Handbook of hydraulic resistance (Moscow: Mashinostroenie) 672
[6] Siegel R and Howell J R 1992 Thermal Radiation Heat Transfer (USA: Washington) 1072
[7] Mikheev M A and Mikheeva I M 1977 Basics of heat transfer (Moscow: Energy) 344
[8] Bird R B, Stewart W E and Lightfoot E N 2002 Transport Phenomena (John Wiley & Sons, Inc.) 898
[9] Vavilov I S, Lukyanichik A I and Yachmenev P S [and others] 2017 Study of heat exchange in a capillary gas heater with graphite resistance element Dynamics of Systems, Mechanisms and Machines 5 pp 21–31