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The small-size ionic-plasma engine for nanosatellites

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Abstract

The miniature ion-plasmatic engine for Cube Sate nanosatellites is described. The working body is the mercury ions received from metal mercury by radiation from its cesium source. The offered construction allows NS trajectory parameters to be changed, to compensate oscillating and rotational motions of the device. Examples of calculation of the IPE some parameters are given.

Keywords: *Nanosatellite; the ionic engine, mercury - caesium alloy; correction of a trajectory of the movement of the satellite.*

Nomenclature

SA	space aircraft
IE	ionic engine
APP	application program package
PCS	polar coordinate system
CCS	cartesian coordinate system
NS	nanosatellite
LRE	liquid reactive engine
WC	working chamber
P	thrust of IPE

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I_{sp}	specific impulse of thrust
η	efficiency
N	power of the IPE power source
U^+	acceleration voltage
i_{eff}	current of an ionic bunch
η_d	efficiency taking into account divergence of an ionic bunch from a nozzle
m*	full expense of a working body
j_i	density of an ionic bunch
e	elementary charge
α	half of a corner of divergence of an ionic bunch
T_i	temperature ionic components
U_P	plasma potential in WC of rather this electrode
η_m	coefficient of ionization of a working body

1. Introduction

Development of small spacecraft's (SSC) including nanosatellites, allows a set of scientific and technological problems in space to be solved. The cost of SSC is much lower than the cost of heavy devices that allows reducing losses at dead start or at early failure in use [1]. Owing to the relative simplicity of SSC also the time of their design and production are significantly reduced. The analysis of current trends of development of the market of KA shows [2] that SSC weighing from 100 to 500 kg placed on low (to 1000 km) orbits can be used for a number of systems, such as mobile telecommunication systems, radio navigation, and also monitoring of Earth, atmosphere and near-earth space. The share of the launched heavy space crafts (SC) (weighing from 1 t and above) constantly decreases and now makes no more than 30% of total quantity of the initial SC [3].

Currently, the following classification of SSC is accepted:

- Small satellites - type of artificial satellites of the earth with small weight and the size. Satellites with a weight less than (0.5 ¸ 1) tons are usually considered small. There is also more detailed classification of types depending on weight. The start of small satellites into an orbit can be made by simpler rockets (for example, RC on the basis of IBM) or as additional loading on normal satellites.
- Mini-satellites have full a weight (together with fuel) from 100 kg to 500 kg. Also satellites weighing from 500 kg to 1000 kg sometimes carry the term "easy satellites" to "mini-satellites". Such satellites can use the platforms, components, and technologies of normal "big" satellites. Mini-satellites are often understood with the general definition "small satellites".
- Microsatellites have a full weight from 10 to 100 kg (sometimes the term is also applied to heavier devices).
- Nanosatellites have weight from 1 kg to 10 kg. The latter are often designed for work in a group, some groups demand the existence of a larger satellite for communication with Earth.
- Pico-satellites is the term for satellites with a weight from 100 g to 1 kg. These are usually designed for work in a group, sometimes with existence of larger satellite. Those with a volume of 1 liter and a weight of about 1 kg are satellites of the CubeSat format and can be considered as either large pico-satellite, or easy nanosatellites. CubeSat are started in several units at a time and have several tens of thousands of dollars removal cost.
- Femto-satellites have weight of up to 100 g. As well as pico-satellites, these belong to the midget spacecraft category, Satellites of a poketsat (literally pocket) format have a weight of several hundred or tens of grams and a size of several centimeters and can be considered as either femto-satellite, or easy pico-satellite. Several poketsat can be arranged and started in the container place and at the price of one CubeSat , that is for several thousands of dollars each one.

Modern nanosatellites differ rather significantly in functionality, despite the small size. Their scope is wide - from Earth remote sensing to space observation:

- working off of the latest technologies, methods and hardware-software solutions;
- educational programs;
- environmental monitoring;
- research of geophysical fields;
- astronomical observation.

Small spacecraft can be used for the following purposes:

- research of communication systems
- calibration of RS and optical systems of control of a space (including passive SC)
- Remote Sensing of Earth (RSE)
- research of rope systems
- educational purposes.

2. The small-size ion-plasmatic engine for nanosatellites.

In recent years views of areas in which SSC can be used have been reviewed significantly. So, SSC are more and more widely used for a solution of problems of communication and telecasting, including on geostationary earth orbits (GSO). According to authors [2; 4] now already up to 25% of geosynchronous SC have a weight of less than 500 kg.

Achievement of payback of the tasks solved by SSC weighing 150-600 kg requires extension of their term of active existence (TAE) to 5 - 10 years [5]. For this purpose, it is necessary to equip MKA with electro reactive engines of low power (up to 500 W). As such, HFIE engines of 150- 500 W can be used.

Electro reactive engines (ERE) opened a new direction in the construction of a space engine [6]. ERE differ from the existing space engines working at chemical fuels. These have a higher profitability, but at the same time considerably smaller thrust-weight ratio, a possibility of receiving small unit impulses and a large number of inclusions. At the same time, the division of power sources and working substance in ERE and the use of an electromagnetic field for acceleration of the working substance allows specific impulse to be increased considerably (on one-two orders), and respectively the profitability of ERE in comparison with chemical reactive engines. This predetermines the areas of applicability of ERE for space aircraft with long times of active functioning (5 - 10) years.

On the other hand, considering NS sizes like Cube Sat, it is possible to install only miniature IPE on such devices, developing thrust at the several watt level. Already today space crafts in the form of a cube with an edge of ten centimeters receive their own ion engines for correction of an orbit. It should be noted that the micro motor as a rule has the size of about a human nail and does not occupy more than a third of internal volume of the satellite. It is clear, that these circumstances complicate the management processes of a NS and considerably increase the time of its movement along the set trajectory. For solution of such tasks, it is reasonable to report NS with an initial impulse in the set direction with an initial speed of an order (0.5 - 2) to m/s by means of magnetic-induction system of start (department) [7].

With this organization of the movement of NS in a zone, for example, IPE ISS set onboard the satellite will play a role of engines of orientation - to adjust a trajectory. For effective work of such MISO + NS complexes, the magnetic-induction system of separate should have an opportunity to orient the main axis of NS in the set zenith and azimuthal directions concerning the coordinate system connected with a space station. For this reason MISO of this kind contain microprocessor management systems [8] connected with the ISS onboard computer modules.

The power (power supply) of spacecraft with a resource of (1 - 20) will be a major problem for years. Engines of small thrust which carry out correction and stabilization of such space craft possess some features, for example, a long resource, high reliability, optimum "price" of thrust (the relation of power expenses to thrust unit). To provide a long-term resource it is necessary to reduce the temperature of constructive elements of plasma propulsions unit, plasma should not interact with construction elements. Generally the speed of the expiring plasma (characteristic speed) defines a specific impulse of the propulsion unit. The higher the value of characteristic speed, the higher the specific impulse. For implementation of long programmers in space it is necessary to have reliable, highly effective electrical rocket engines with plasma exhaust speeds (103 - 105) m/s and more.

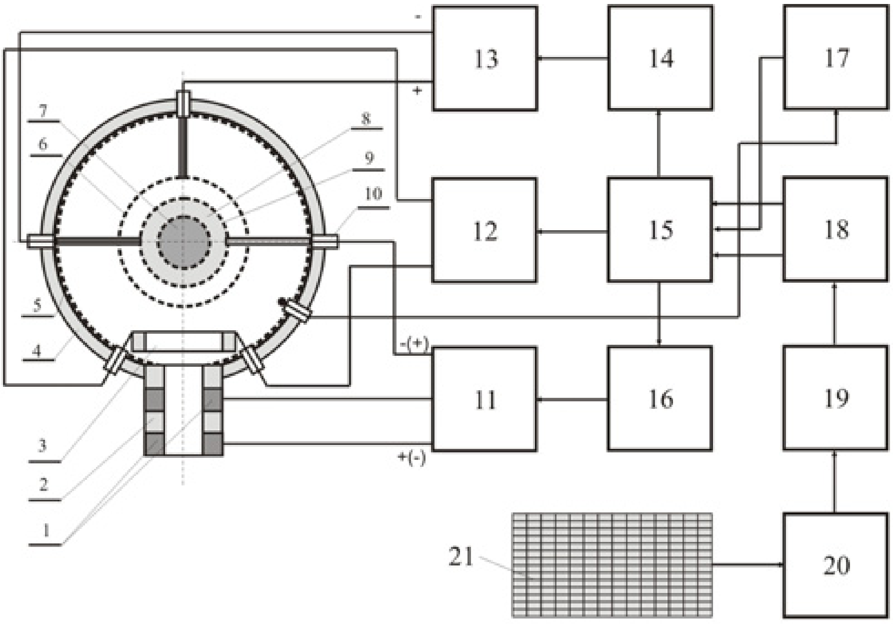

Fig. 1 Sketch of the laboratory model of miniature IPE for NS

It is obvious that micro and nanosatellites (NS) are at the new stage of development of technologies for miniature spacecraft's. Small spacecraft's are already actively used today for remote sensing of Earth, environmental monitoring, the forecast of earthquakes, research of an ionosphere, etc.. Profitability is considered the main advantage of IE. As ions have a speed of 10 times more the exhaust speed of gases from the rocket engine, for change of speed of the spacecraft on the set value they require 10 times less fuel. A lack of IDES is very small thrust which does not allow them to be used for take-off from Earth, and also the maneuvers demanding fast changing of a trajectory. The early developed micromotors of the ionic type include the first ferromagnetic and ion engine (MTI), the compact flat accelerator, the thruster created by Paulo Lozano - professor of department of aeronautics and astronautics in MIT, respectively. Specialists from the polytechnical school of Lausanne created the ionic engine – Micro Thrust, etc. Ideas of this kind are able to change slightly the nature of the movement of NS during rather big interval since their thrust makes an order of units of watts. The working body represents, as a rule, ionic liquid. In spite of the fact that the exhaust speed of ions in such IE makes more than 11 km/s thrust usually does not exceed 1×10^{-6} N. Thus development of more power armed micro IE for NS for the tasks considered above is very topical.

Fig. 1 shows the sketch of the miniature IPE developed by the authors for NS and the skeleton diagram of the microprocessor module of management of IPE operation modes. Metal mercury - 8, placed in the mesh container - 9 is a source of ions in this IPE. Primary ionization of atoms of mercury is carried out by means of a radioactive source γ - radiation, on a basis ^{137}Cs - 7, placed in the container. Depending on the selected IPE parameters - pulling forces, the IPE sizes, ways of management and so forth, it is possible to use mercury - a cesium alloy (mix). At cesium disintegration, at the first stage reaction ${}^{134}_{55}Cs \rightarrow {}^{134}_{56}Ba + e + \overline{\nu_e}$ then there is a disintegration ${}^{134}_{56}Ba$ to selection γ - photons is implemented, thus, in the course of ionization of atoms of mercury participate e^-, γ . At the same time due to energy of photons and electrons there is some warming up of a working body. Selecting masses ${}^{134}_{55}Cs$, ${}^{200}Hg$, try to obtain required concentration of ions ${}^{200}Hg^{+,(++)}$ in the IPE working chamber between spherical electrodes - 5, 9. Depending on construction of IPE, its sizes partial pressure in the working chamber of mercury in the set mode makes (100 Pas - 100 kPa). In the working chamber - 4 there is also spherical electrode - 6 which carries out a role of a collector of negative ions, electrons. The chamber should be made from high-strength ceramics (polycrystalline glass), for example, from aluminum oxide (50%) and silicon nitride (50%). It is reasonable to execute electrodes of titanium, an electrode - 5 by sputtering, and electrodes - 6, 9 and the container for a radioactive preparation by a stamping method from a grid.

The process of ignition of the plasma looks as follows. When giving a power voltage between the closely located basic and lighting electrode there is a glow discharge that is promoted by the small distance between them which is significantly less than the distance between the main electrodes, therefore, the breakdown voltage of this interval is also lower. Emergence in a cavity of IPE of rather large number of charge carriers (free electrons and positive ions) promotes breakdown of an interval between the main electrodes and ignition between them a glow discharge which almost instantly passes into the arc discharge.

Forming of an ion-plasma stream in this IPE is carried out by means of the nozzle representing the linear accelerator which consists of ring insulators - 2 and accelerating electrodes - 1. Insulators are made from high-temperature ceramics, and the accelerating electrodes from titanium alloy. In the chamber the solenoid - 3, which serves to prefocus the working body can also be placed (this is defined by the IPE sizes), it somewhat increases the flux density on a nozzle input. Electrodes - 5, 6, 9 and outputs of the solenoid - 3 and the temperature sensors are connected with the module of management of operation modes; the corresponding conductors through insulators through passage - 10.

The principle of work of this miniature IPD is as follows. In an initial status on an electrode - 5 positive constant potential, and on an electrode - 6 negative is given, thus, the working body is locked in WC. For locking negative components the corresponding potential difference between electrodes - 6, 9 from a separate constant voltage source moves. For reduction of IPD in operating conditions between electrodes - 6, 9 a variable pulse tension is put (a meander with a frequency of 200×10^3 Hz). As a result in the working chamber a discharge similar to discharge is excited in high pressure mercury lamps. On the solenoid - 3 current from the managed source of a direct current moves, and the alternating surge acceleration voltage is put to accelerator electrodes - 1 and to an electrode - 5. In this case acceleration of ions ${}^{200}Hg^{+,(++)}$ is carried out in two inter electrode intervals - electrodes 5 and 1. Changing amplitude and frequency of a meander of impulses it is possible to regulate the value of thrust of IPE.

The microprocessor module of management of operation modes of miniature IPD consists of the managed modules: high-voltage pulsed source - 11, the managed current regulator - 12, a high-voltage source - 13, shapers of control impulses - 14, 16, the microprocessor module - 15, temperature analyzer in RK - 17, the shaper of power voltages - 18, the accumulator block - 19, the controller of solar panels - 20, the solar panel 21. The high-voltage pulsed source - 11 on commands of the microprocessor develops either constant cut-off voltage between electrodes - 6, 9, or the accelerating alternating voltage (2500 ÷ 3500) B, between electrodes - 5, 1, through the corresponding voltage divider. As temperature in the ISS zone can change in limits (-100 ÷ +100) C °, respectively change, temperature, pressure, and to a lesser extent concentration of ions ${}^{200}Hg^{+,(++)}$ in WC, according to the known ratio $p = nkT$, a problem of the microprocessor module to compensate these changes, regulating current in the module - 12, parameters of tension in modules - 11, 13. In the elementary case, as control signals for these purposes serve these temperatures received from the analyzer - 17 in WC IPE which receives a signal from the temperature sensor placed in the working chamber.

3. The main estimated ratios for small-size IPE

Unlike calculations of IPE in which, a working body are gases - hydrogen, xenon and so forth [9], calculation of parameters of mercury-cesium IPE is very complicated. This results from the fact that it is quite difficult to evaluate an ionization rate of atoms of mercury component e^-, γ radiated by a radioactive preparation. Such parameters as a rule, are decided from bench tests, on use of this (specific) preparation ${}^{137}Cs$ as each of them is characterized by individual values of density of flows, energy γ - photons and electrons. But, nevertheless, provided that masses

${}^{134}_{55}Cs$, ${}^{200}Hg$, is picked up optimum, i.e. γ - photons are almost completely absorbed by a mercury layer - only at the same time the maximum ionization of atoms of mercury is observed it is possible to offer the following method of calculation of the main performances of IPE of the offered type. Treat the main characteristics of the engine [9]: specific impulse of thrust I_{sp} , thrust P , and performance coefficient η . These values are connected among themselves by a ratio:

$$N = \frac{I_{sp}P}{2\eta} \tag{1}$$

Let's notice that efficiency value as a rule appears in limits. In this case - power the consumed IPE which consists of the power of a flow of ions, the power of high-voltage power sources and power consumed by the solenoid that is:

$$N = N_i + N_h + N_c + N_s \tag{2}$$

These values can be determined as follows:

$N_i = U^+ i_{eff}$

Where U^+ - acceleration voltage, i_{eff} - an effective beam current,

$N_h = C_i$

Here, C_i - energy costs of a source of high tension on "additional" ionization of atoms of mercury, this value depends on coefficient of ionization of a working body η_m at the expense of a source of high tension, it can be evaluated in the form of [9, 10]: $\eta_m = \dfrac{i_{eff}}{m^*(q/M_i)}$, m^* - a full expense of a working body, q - a mercury ion charge, M_i - the mass of an ion of mercury. Thrust of IPE can be defined by a ratio:

$$P = \eta_d \frac{i_{eff}}{q/M_i} I_{sp} \tag{3}$$

In this case η_d - efficiency taking into account divergence of an ionic bunch from a nozzle (estimates losses of an impulse of thrust at the expense of a bunch defocusing), usually evaluate this value as: $\eta_d = \dfrac{1+\cos\alpha}{2}$, α - half of a corner of divergence of an ionic bunch.

The specific impulse can be evaluated from a ratio:

$$I_{sp} \approx \eta_m \sqrt{2(q/M_i)(U^+ + U_p)} \tag{4}$$

Where U_p - plasma potential in WC concerning an electrode - 6.

The current density of an ionic bunch through a nozzle is evaluated by means of expression [7]:

$$j_i \approx 0,43 e^+ n_q \sqrt{2T_i / M_i} \tag{5}$$

Here j_i - density of an ionic bunch, e^+ - an elementary charge, n_q - concentration of ions, T_i - temperature ionic components. Value U_p can be determined approximately as [8]: $U_p \approx -(T_i/e)\ln(0,86)\sqrt{\pi m_e / M_i}$, where m_e - the mass of an electron.

For a flow of ions in RK where primary bunch forms, it is possible to construct a mathematical model which should consist at least of three equations [9, 10]:

- Poisson equation - describes the electric field created by electrodes - 5, 6 (stationary approach),
- motion equation of a positive ion in an electrostatic field,
- continuity equation (charge conservation law), i.e.:

$$\Delta\varphi = \left(\frac{\partial^2\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{\partial^2\varphi}{\partial z^2}\right) = j_i / \varepsilon_0 \sqrt{\frac{2e\varphi}{M_i}},$$

$$M_i \frac{dv}{dt} = -e\nabla\varphi, \qquad (6)$$

$$\overline{\nabla}(en_i\varphi) = 0$$

It is necessary to impose the following boundary conditions on this system of equations:

- electrode potential in each point is identical, the electrodes geometry remains;
- on a symmetry axis in the direction of a normal to axis grad (φ) = 0 (Neumann's condition);
- distribution of potential in a transitional layer can be selected proceeding from a technique of the calculations described in [10, 11];
- border of a zone of neutralization of primary bunch of ions.

Mathematical modeling, on the basis of the considered expressions gives the chance to receive the following evaluation values of some parameters of the IPE this type:

- if to accept temperature of ions of mercury $T_i \approx 5\ eV$ (vapors of mercury formed by thermal heating, diameter of WC made 30 mm),
- vary acceleration voltage in limits ($U^+ \to (1000,...,2500)\ V$), the beam current, for diameters of a nozzle of $\phi = (1,...,3)$ mm reaches values $i_{eff} \approx (80,...,140)\cdot 10^{-3} A$.
- the maximum thrust received on this laboratory model made a value of (5 - 10) ×10^{-6} N that is explained in our opinion by a low performance of ionization of metal mercury the thermoheater.

4. Conclusion:

1. The miniature that is developed is ionic - the plasma engine for nanosatellites which allows the movement of the NS after its separation from the MISO system to be managed effectively.
2. The method of calculation of key parameters of this engine are created; mathematical modeling of some of its characteristics is carried out.

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