# NEW GENERATION OF ELECTRIC THRUSTERS

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## ABSTRACT

Over the last years there grows the need in small satellites that may be used in space for a long time. One of the drives for small satellites to come is advent of light-weight and long-life solar arrays which are necessary for electric propulsion having long service life. Such a combination of new solar arrays and economical electric thrusters allows to relatively cheaply, fast and reliably perform many space missions which can't be performed using other technologies.

This paper describes the developed at MAI electric thrusters of 3 types: ion thruster, closed electron drift thruster and colloidal one. Performance of all these thrusters matches the best world performance for small electrostatic thrusters. These days some of these thrusters are being tested at other organizations.

## SMALL SATELLITES SYSTEMS

Analysis of space systems development shows that recently there began intense development of new generation satellites with mass of 300-400 kg and active life in orbit of 5-15 years. Constellations of such satellites could make up a global system for individual users communications, global computer communications, Earth remote sensing, carry out meteorological researches, detect objects (including mobile ones) at high accuracy.

The most known systems which will be launched in the nearest future are Iridium - 77 satellites, Globalstar - 48 satellites, Orbcomm - 24 satellites. Apart from general purposes, small satellites may be used for special purposes, thus, NATO plans to use them on geosynchronous and Sun-synchronous orbits for observation over the zones where armed conflicts occur.

To be economically efficient, it is necessary that the vehicle orbit life was not less than 5 years.

The main reason limiting the satellite life is effect of ambient environment, first of all, - friction and solar pressure. To compensate for these effects and, hence, increase the satellite orbit life, low-thrust rocket engines are used. The propellant mass necessary for a long-term mission considerably reduces the payload mass, and therefore, the main problem here would be increase of specific impulse.

Conventional chemical microthrusters, both bi- and mono-propellant, have specific impulse not exceeding 3000 m/s and there are practically no ways to increase it.

The situation really changes in case of electric propulsion where acceleration of charged particles is done by means of electric fields. In this case the necessary exhaust velocities may be realized, and hence, propellant consumption will be small but the higher the jet exhaust velocity, the higher is power of the thruster which requires more powerful power plants.

Thus, at higher exhaust velocity the working fluid amount necessary for the propulsion system decreases whereas the power plant mass grows. The optimum exhaust velocity is determined by taking into account the thruster operation time, efficiency and power plant specific mass.

These days there are developed and being in use the power plants on the basis of solar arrays with very good specific performance allowing to consider them as promising on-board energy source for spacecraft.

For instance, a number of ESA spacecraft use SiBSFR photovoltaic converters. On the orbits close to the Earth's one these cells allow to produce over 0.2 kW/m$^2$. Use of Ga-As-Ge cells may result in the solar array specific mass to be (including structural elements) at the level of 11.5 kg/kW, and use of silicon cells - even 10.5 kg/kW. At this specific performance and power consumption of 0.5-1.0 kW the corresponding masses and areas of solar arrays practically do not change the spacecraft layout and look.

These achievements in photovoltaic technology allow to sometimes increase the working fluid exhaust velocities up to 35,000-50,000 m/s. This is a difficult task, especially for small electric thrusters which are likely to be used on small spacecraft. This paper discusses results of such thrusters' prototypes development carried out at MAI.

If compensation for the effect of external environment on a 500-kg satellite requires increment of characteristic velocity about 200-500 m/s, then in case of electric propulsion on board this will take a few kg of xenon. Attempts to solve this problem using conventional chemical microthrusters result in propellant mass exceeding that of the satellite which makes it impossible to use them on long-life small spacecraft.

Solar pressure effect is especially essential for a slightly shaded Sun-synchronous orbit. So, for a 500-kg satellite with the solar radiation impact area of 2 m$^2$ monthly loss of speed will make up $4.5 \cdot 10^2$ m/s. Its compensation is possible by means of the 5-mN thruster operating about 12 hours a month.

The electric propulsion capabilities for orbit correction may be illustrated with the following example. Transfer of an 800-kg satellite from the Sun-synchronous orbit (altitude of 480.1 km, inclination 97.17°) into the orbit of 466 km altitude and 97.27° inclination (the area observed with optical instruments will significantly change then) requires operation of an 8-mN electric thruster (240 W of power) during 174 hours which takes only 2 kg of xenon.

## ELECTRIC PROPULSION THRUSTERS

Out of the many examples some of which are adduced above it is possible to make a conclusion that long-living small satellites are likely to use 2-8-mN thrusters having specific impulse more than 35,000 m/s and thrust cost no more than 30 kW/N. The required life of such thrusters must be no less than 10,000 hours. Various types of electric thrusters have flown in space for a rather long time[1]. However, their power was of the order of 1 kW and above. Reduction of the single module power will worsen the thrusters performance, and therefore an important problem is development of low power electric thrusters with high performance.

One of the most perspective electric thruster types is ion thruster (fig.1). The working fluid is fed into the discharge chamber and its atoms are ionized by electron impact in gas discharge burning between the cathode and anode. To enhance the ionization efficiency, magnetic field created by magnetic system is imposed onto the discharge. Ion extraction from gas discharge and ion beams formation of low energy and current density is done by means of a three-electrode electrostatic system consisting of the

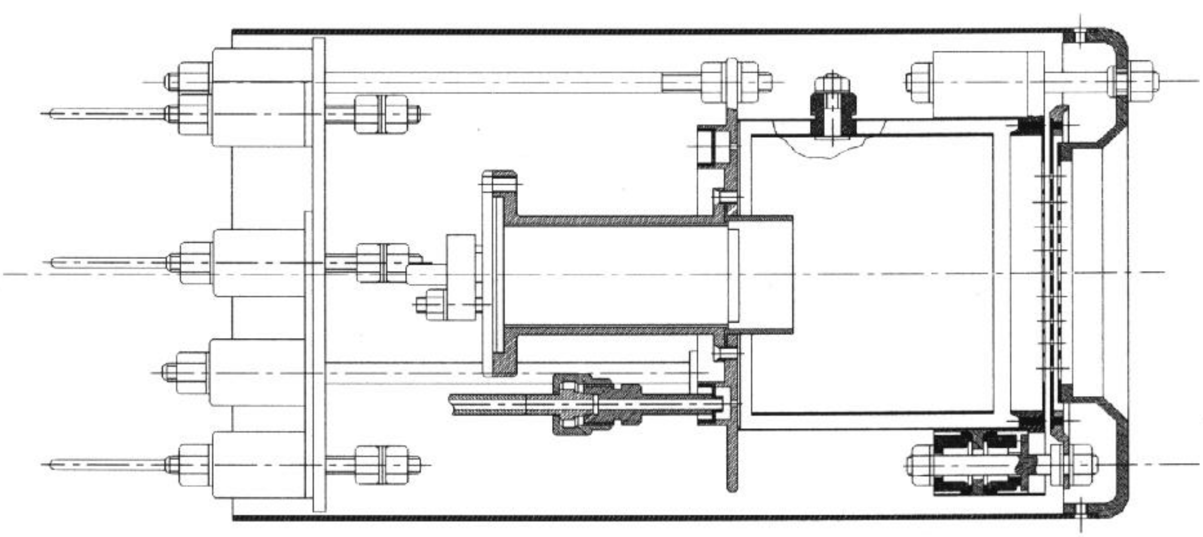

Fig. 1

emission electrode, accelerating electrode and output electrode. At the thruster's outlet there is placed a source of electrons - a neutralizer. The thruster's efficiency depends on how much power is required to produce one ampere of ion current which gives the thrust. Reduction of the discharge chamber dimensions worsens the ionization conditions and results in increase of the relative surface area of ion recombination, therefore, when designing a low power ion thruster, it is very important to correctly choose the configuration and strength of magnetic field, and also improve conditions of ion extraction from the gas discharge plasma through the accelerating system electrodes at simultaneous reduction of neutral flux from the GDC. These conditions are realized by means of the accelerating system design.

Moscow State Aviation Institute and Keldysh Center have developed the 2-5-mN ion thruster having specific impulse of 35,000 m/s and ~50 % efficiency.

Another electric thruster type successfully used in space is the stationary plasma thruster (SPT). Its operation is basically generation and acceleration of ions in gas discharge burning in crossed electric and magnetic fields[2]. Ion acceleration in plasma at the quasi-neutrality condition removes limitations of volumetric charge for ion extraction from an elementary volume which allows to obtain current densities greater than those in ion thrusters. The conventional SPT scheme (see fig.2) contains the following ring-type elements: dielectric chamber with the anode inside it simultaneously serving the working fluid distributor; a C-shape magnetic system producing mainly radial magnetic field in the discharge chamber; cathode-compensator producing electrons to maintain the discharge and neutralize the ion flux leaving the thruster. Presence of radial magnetic field prevents the electrons from free flowing towards the anode and allowing them to mainly move in azimuthal direction in case there is a longitudinal electric field. The electrons move to the anode as a result of various collisions. The magnetic field parameters are chosen so that the electrons would be maximum "magnetized" and that there would be practically no cycling ions. Magnetic field profiling makes it possible to create optimum distribution of the electric field in plasma volume.

Design simplicity, limited number of power sources, reliability in operation allow to consider SPT as one of the most promising electric thrusters for broad use in space, in particular, on small satellites. In the latter case, limited onboard power requires development of low-power thrusters.

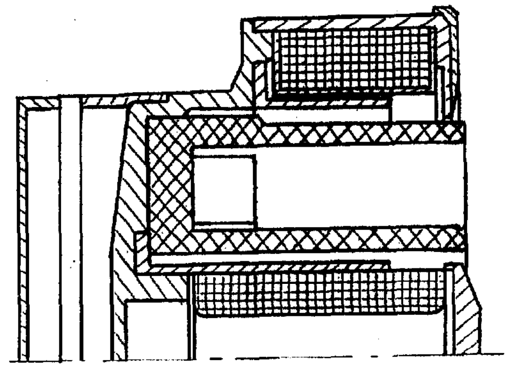

Fig. 2

Low-power SPT development is connected with the necessity of reducing the characteristic dimensions of the model. It is determined, first of all, by that for SPT a higher gas ionization efficiency in the accelerating channel needs the following condition to be matched[5]:

$$\lambda_i = \frac{V_a}{\langle \sigma_i V_e \rangle n_e} < L \ , \quad (1)$$

Where $V_a$ - longitudinal atom velocity,

$\langle \sigma_i^* \ v_e \rangle$ - ionization speed factor dependent on the kind of working fluid and temperature (energy) of electrons in plasma,

$n_e$ - plasma mean concentration in the accelerating channel,

L - characteristic size of the acceleration zone.

For existing SPT models the best efficiency is reached at optimized by topology magnetic field. Reduction of the thruster dimensions makes it far more difficult to match this condition. The problem is that, as the experiments show, the optimum magnetic induction values ($B_{opt}$) increase with decreasing characteristic dimensions of the thruster (L or $b_c$,) so that for the first approximation:

$$B_{opt}\, b_c \cong \text{const} \qquad (2)$$

Therefore, reduction of the size requires to reduce the cross sections of magnetic conductor elements not proportionally to L but slower. Thus, the optimum ratios of the magnetic system elements is not kept properly and optimum configuration of magnetic field force lines and induction is not obtained. Complexity of ensuring the required magnetic field topology at a standard ratio of channel width to its mean diameter being ~1:4 begins to clearly manifest itself at d≅40 mm.

Developed at MAI SPT models for power below 300 W with thrust of 10-20 mN ensure the thrust efficiency level of 0.4 at specific impulse of 11,000 m/s and the thrust cost of 18.5 kW/N. Further performance improvement is possible in case of additional research done on magnetic system optimization[6].

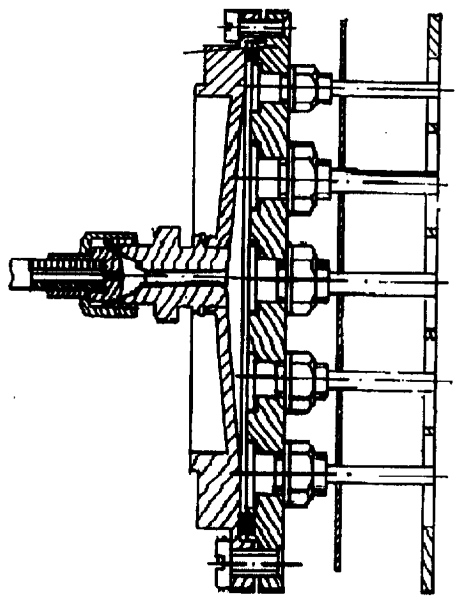

Fig.3

The third type of thrusters which can be used on small satellites is colloidal thruster (fig.3). This thruster electrostatically sprays the fluid held in the capillary tubes 1 under action of the potential difference between them and the accelerating electrode 2. In fact, this type of thruster realizes the same acceleration mechanism as in ion thruster but instead of ions there go particles a hundred or thousand times heavier than ions. MAI has developed a monoblock of such a thruster of 30 W power, up to 10 mN thrust and ~20,000 m/s specific impulse. Modular design allows to obtain the thrust ranging from a portion of mN up to several mN.

**RESUME.**

The materials discussed in this paper show that there begins a new era in space technology development. Small spacecraft with light solar arrays and economical and reliable electric thrusters, in particular, developed at MAI will allow to successfully perform in the nearest future a number of very important space missions.

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