The influence of the working fluid type on the parameters of the ion engine

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Abstract. Nowadays, the level of technological progress, the foundations of which were laid in previous decades, has made it possible to practically master the use of near-earth orbits and conduct separate research trips beyond them. Further steps, including expanding the functionality of space vehicles in near-Earth orbits, the creation and regular operation of a lunar space base, large-scale planetary and other bodies of the solar system exploration, and sounding of deep space, require, first of all, a sharp increase in the capabilities and efficiency of space transport systems. A further increase in the flow rate of the working fluid requires an increase in its specific energy content, that is, conversion to a plasma state, which is implemented in ion engines. In ion engines, ion beams are accelerated in an electric field organized by electrodes. The volume charge in the accelerating gap is not compensated; this serves as one of the restrictions on the current density in such a beam. In the present work, we took hydrogen, deuterium, helium, nitrogen, argon, krypton, xenon as the working fluid, for which the dependences of the optimal ion emission current density on the distance and voltage between the electrodes of the accelerating gap, breakdown voltage of distance between the electrodes, specific thrust of the specific impulse, specific impulse of the mass number of ions and others were calculated, and the most promising and effective working fluid was determined.

Awareness of the limited resources of the earth and the vulnerability of the environment, both in relation to the uncontrolled impact on it of the results of the vital activity of the Earth's population, and the dangers of external influences, pushes mankind to spread its activity beyond the planet. An important direct incentive for this activity in the current geopolitical structure of terrestrial civilization is the growing connection of the country's space potential with the reliability of ensuring its sovereignty.

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From the very beginning of the development of astronautics, there was a clear understanding of the limitations of reactive chemical engines and the need to attract new ideas. The desire to be able to "give tremendous rate ejected from the jet unit particles" becomes understood when looking at a Ciolkovsky K. E. formula: [1]

\[ V_x = V_{out} \cdot \ln \frac{M_{const} + M_{out}}{M_{const}} \]  (1)
Where is the characteristic speed, i.e. the speed that a rocket would gain if it moved in a straight line only under the influence of its propulsion system (without any external forces), - the velocity of the expiration of the working fluid, - the mass of the ship, - the mass ejected from the nozzle. In this case, the thrust developed by the rocket engine is proportional to the rate of the flow of the mass of the working fluid and the rate of its expiration:

\[ F_t = V_{\text{out}} \times \frac{dM}{dt} \] (2)

From formula (1) we can conclude that the effect of the total mass flow rate is relatively small compared to the rate of its ejection. Ciolkovsky immediately drew attention to it, noting that the technical possibility of saving the working fluid mass, which was not discovered at that time: “Perhaps, it will be possible over time to give enormous speed to particles ejected from a jet device with the help of electricity...” [1]

Boost of working fluid speed expiration requires increasing in its specific energy, i.e. the translation into the plasma state using “electric power”.

A solution to this problem can be reached by accelerating charged particles by an electric field. Two extreme cases are possible: acceleration of ions drawn from a plasma (ion engines) or acceleration of ions in a plasma by constant or alternating electric fields (plasma jet engines, PJE). Therefore, the possibility of “imparting greater speed to the particles ejected from the jet device” originates from the moment of the appearance of ionic and plasma engines.

Considering closely the most researched and widely used in the space practice ion engine (IE), which is an adaptation of the sources of ion beams used in physical experiments [1] to the specific requirements of the rocket engine on the basis of which the designed megawatt level power spacecraft (SC).

An IE usually consists of three main parts: an ion emitter, an electrostatic accelerator with one accelerating gap, and an electronic charge compensator. The presence of a compensator is a specific requirement of space conditions. The emitter usually is a gas discharge chamber (GDC) where ionization of the working gas takes place; An electrostatic accelerator is a system of perforated electrodes that form an ion-optical system (usually a 2 or 3 electrode IOS), which, when applying the necessary electric potentials to them, extracts ions from the gas distribution complexes and accelerates them with the simultaneous formation of a beam-directed flow ions, its own space charge and the current of which, after exiting the IOS, must be compensated by injection of the corresponding electron flux.

In this paper, we considered the RF IT-450 engine.

![Fig. 1. ID circuit with a three-electrode IOS and GDC based on RF discharge](image)

In fig. 1 a diagram of an ion engine with a GDC based on an RF discharge is shown, which has the advantage of “cathode-free” over a GDC with direct current discharges, the limitation of the service life of which is precisely determined by the failure of the cathodes. A negative potential at the intermediate
(accelerating) electrode is necessary to prevent the backward flow of electrons to the emission electrode (perforated GDC wall, through which the ions of the formed beam pass through the apertures). The third electrode, shorted to the hull of a spacecraft (SC), is often made in the form of a ring covering the entire beam; sometimes it is a ring electronic source - a compensator. For GDC, a change in the working class does not lead to improved combustion characteristics, since the ionization cross section is almost the same. Also, an important point is that gas ionization is spent much less energy, approximately several watts, than is spent on the acceleration that occurs in an ion-optical system.

IOS is a key node that determines the energy efficiency and reliability of the ion engine. It is here that the main energy input into the working fluid is made; it is its electrodes that are the most energy-stressed structural elements, the reliability requirements of which impose basic restrictions on the specific power of the engine. One of the main limitations is the breakdown voltage limit in the gap ($U_{\text{operating}} = 0.8 \ U_{\text{crit}}$).

Plasma flow from the volume of the gas distribution system comes to the inner surface of the emission electrode. The density of the ion current saturation on them is determined by the well-known formula [2], which is given here in a form convenient for practical use:

$$j_i = \frac{0.6 \ Z n_i \cdot 1.3 \cdot 10^6}{6.25 \cdot 10^{18}} \sqrt{\frac{2 T_e}{\mu}}$$

where $Z$ is the charge of ions, $n_i$ is the density of ions in the plasma of the gas distribution complex (cm$^{-3}$), $T_e$ is the temperature of the electrons in the discharge (eV), $\mu$ is the mass number of ions (the ratio of the mass of the ion to the mass of the proton).

Ions that have passed the aperture fall into the accelerating gap, which, as a first approximation, can be considered as an equivalent flat diode, the maximum current density through which is given by the Child – Langmuir law (law 3/2) [3]:

$$j_{3/2} = 5.4 \cdot 10^{-8} \sqrt{\frac{Z}{\mu}} \left(\frac{U_{\text{acc}}}{a^2}\right)^{3/2}$$

where is the accelerating voltage (V), is the accelerating gap (cm).

Of course, the density of the ion current coming from the GDC to the emission electrode is determined by the plasma parameters in the GRC, so the meaning of restriction (4) is that, at a higher current density, the ion flux will not be formed properly; it will get on the accelerating electrode and will cause a destructive breakdown. When the current density decreases against the optimum, the beam is “refocused” and, generally speaking, can also cause breakdown.

Therefore, the condition for the normal operation of the IOS of the engine is the coordination of the current densities coming from the plasma and mastered by the accelerating gap.

However, in real IOS, unlike an ideal flat diode

- the ion beam has a limited transverse size, depending on the diameter of the aperture of the emission electrode;
- the plasma boundary is not flat and its curvature changes with a change in the plasma density in the GDC;
- “Sagging” of the equipotentials in the aperture of the accelerating electrode creates a defocusing field configuration at the exit from the accelerating gap;
- in real conditions, there is a requirement for high voltage interelectrode gap. [1]

Numerous experimental results obtained during the development of powerful ion sources as part of thermonuclear research [2] are consistent with dependence (5) at $C=8$ and $d=0.8$. 


where, \( d_1 \ [cm], \alpha < 1 \).

The limited transverse size of the ion beam leads to the appearance of a transverse electric field created by its own space charge of the beam, which causes its divergence. Partially, this divergence is countered by giving a slant to the edge of the aperture in the emission electrode, which ensures the transverse component of the electric field of the accelerator gap, directed against the transverse field of the space charge (Pierce optics). This effect works at a distance of the order of the thickness of the electrode. Further counteraction of the divergence due to the action of the space charge and compensation of the action of the defocusing field configuration at the exit from the accelerating gap are carried out by the organization of the concavity of the plasma boundary, which is achieved by reducing the density of the extracted current compared to the defined "law 3/2" [1]:

\[
\mathcal{J}_{\text{opt}} = 0.7 \cdot \mathcal{J}^{3/2}
\]

Due to the above mentioned, the characteristic dimension (d) of equivalent planar diode for real ILE does not coincide with an interelectrode distance, within the expression (5). The relationship between these two parameters is determined by the design conditions for the implementation of the IOS electrodes. Empirically this relationship can be defined by the following equation [1]:

\[
d = 0.5 \cdot r_1 + t_1 + d_1 + 0.5 \cdot r_2
\]

where, \( r_1 \) is the apertures in the emission electrode, \( t_1 \) is the thickness of the emission electrode, \( d_1 \) is the gap between the electrodes, \( r_2 \) is the radius of the aperture in the accelerating electrode.

In addition, for reliable operation of the IOS of the engine, the voltage between the electrodes forming the accelerating gap should be less than the circuit breach.

\[
U_{\text{acc}} = \beta \cdot U_{\text{circ}}
\]

where \( \beta < 1 \).

The evaluation results of the reduced formulas for different grades of working fluid (helium, krypton, nitrogen, xenon, hydrogen, argon, deuterium), made with reference to the engine ILE RF IT-450, are presented in Figures 2-5.
Fig. 2. The dependence of the optimal current density of ion emission on the distance between the electrodes of the accelerating gap for different working gases.

Fig. 3. The dependence of the optimal current density of ion emission on the voltage at the electrodes for different working gases.
Fig. 4. The dependence of the breakdown voltage on the distance between the electrodes of the accelerating gap for different working gases.

Fig. 5. Relation of the specific impulse to the mass number of ions.

The highest values of specific impulse are achieved when hydrogen acts as a result of the working fluid. The largest value of the breakdown voltage at the same distances between the electrodes is observed when using helium. The highest ion current density at the same electrode voltages is observed when using hydrogen.

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