

Module With A Multi-Channel Plasma Propulsion System For Small Spacecraft

Background

The invention relates to space technology, in particular to electric propulsion systems with an electric rocket engine (ERE) with no electrode plasma source and an accelerating stage, using a wide range of substances as a working medium, intended mainly for installation on small spacecraft (SSC) for them before launching from the reference orbit to the target orbit, correcting and maintaining the orbit, orientation, unloading the attitude control systems, maneuvers between orbits, removing the spacecraft from the target orbit at the end of its active life (AL).

State of related arts

Known analogue - the invention of the More efficient RF plasma electric thruster (patent US6293090B1, published 25 Sep 2001). The invention relates to electric rocket engines. The invention includes an RF generator, a plurality of emitting elements, a gas-discharge chamber defining the main axis of the engine, a magnetic system, a power source for the magnetic system, a system for supplying a working medium, and a connection with a gas-discharge chamber.

The disadvantage is that the gas inlet is connected to the gas discharge chamber from one of its ends. In this case, the possibility of using the end of the gas-discharge chamber for the outflow of plasma and creating a thrust in this direction is lost. Thus, the volume, mass and power consumption of the propulsion system increase when several such engines are placed to control several axes of thrust, which makes it ineffective or impossible to use them on board a small spacecraft. The use of a plurality of radiating elements powered by a single RF generator to generate plasma in one gas-discharge chamber will lead to the occurrence of instabilities in the volume of the generated plasma, which are associated with the difference in electromagnetic radiation generated by the radiating elements along the channel length, which in turn will lead to a decrease in thrust and efficient motor impulse. The use of many closely spaced radiating elements operating at HF frequencies will lead to the occurrence of parasitic HF capacitive discharges both between the studying elements themselves and between the radiating elements and the magnetic system of the motor due to the occurrence of HF capacitive coupling between these elements, which ultimately will reduce the efficiency of the engine. in particular, it will reduce the specific thrust and specific impulse per unit of RF power supplied, will lead to a decrease in the engine resource due to the destruction of structural elements when they are sprayed by the arising RF capacitive streaks, will lead to the impossibility of the power contribution to the plasma, i.e. to engine failure, because the gas discharge chamber will be

covered with products of sprayed metal antenna and engine elements. Gas injection at the beginning of the gas-discharge chamber will lead to power losses for the processes of re-ionization of the recombined particles of the working fluid along the length of the gas-discharge chamber, which, in turn, will lead to a decrease in the specific thrust and specific impulse of the engine per unit of power.

A known analogue is the invention of the Helicon plasma electric propulsion device (patent CN104405603B, published on 12 Apr 2017). The invention relates to electric rocket engines. The invention includes at least one metal ring constituting the engine housing, the first and second metal flanges, a helicon antenna, a gas discharge chamber, a gas inlet, at least two rings of magnets.

The disadvantage is that the gas inlet is connected to the gas discharge chamber from one of its ends. In this case, the possibility of using the end of the gas-discharge chamber for the outflow of plasma and creating a thrust in this direction is lost. Thus, the volume, mass and power consumption of the propulsion system increase when several such engines are placed to control several axes of thrust, which makes it ineffective or impossible to use them on board a small spacecraft. Gas injection at the beginning of the gas-discharge chamber will lead to power losses for the processes of re-ionization of the recombined particles of the working fluid along the length of the gas-discharge chamber, which, in turn, will lead to a decrease in the specific thrust and specific impulse of the engine per unit of power. The use of a helicon antenna without protective dielectric rings will lead to the occurrence of parasitic HF capacitive discharges on the surface of both the antenna itself and on the surfaces of the engine proposed in the invention due to the occurrence of HF capacitive coupling between these elements, which ultimately will reduce the efficiency of the engine, in particular, reduce the specific thrust and a specific impulse per unit of RF power supplied, will lead to a decrease in the engine resource due to the destruction of structural elements when they are sprayed by the arising RF capacitive divorces, will lead to the impossibility of the power contribution to the plasma, i.e. to engine failure, because the gas discharge chamber will be covered with products of sprayed metal antenna and engine elements.

The closest analogue (prototype) is known - the invention of a low-thrust rocket engine for a spacecraft (patent RU2445510C2, published 20 Mar 2012). The invention relates to low-thrust rocket engines. The invention according to claim 24 of the claims includes a gas-discharge chamber (main chamber) defining the axis of thrust forces, an injector for introducing ionizable gas into the main chamber, an antenna, magnetic field generators, an electromagnetic field generator, a generator for changing the direction of the magnetic field.

The disadvantage is that the invention has only one direction of thrust of the gas discharge channel. The ionizable gas injection injector closes one of the ends of the gas-discharge chamber, which in turn leads to inefficiency in its use, because when applying the proposed method of gas ionization - electromagnetic, plasma can flow out of the two ends of the gas-discharge chamber. When developing an engine for a small spacecraft, in particular, the engine with more than one thrust vector proposed in FIG. 40 and described in clause 60 of the claims of the invention under consideration, the use of only one end of the gas-discharge chamber will lead to an increase in the mass and dimensions of the engine, which, as a result, will lead to an increase in the cost of developing and launching the SSC or to the impossibility of using the device proposed in the invention for use on board the small spacecraft. The proposed antenna device, in particular, the use of capacitively coupled electrodes in it, is inappropriate for use on board the small spacecraft. This is due to the fact that a parasitic capacitive discharge will begin to occur on all elements of the propulsion system and small spacecraft, close to the capacitively coupled electrode, while the capacitive discharge will destroy both the electrodes themselves and the structural elements of the engine and small spacecraft. The problem of the occurrence and consequences of a parasitic capacitive discharge is described in the work of Takahashi, K. (2012). Radiofrequency antenna for suppression of parasitic discharges in a helicon plasma thruster experiment. Review of Scientific Instruments, 83 (8), 083508 (<https://doi.org/10.1063/1.4748271>). Also, the use of a capacitive discharge to ionize the working fluid is an ineffective way of generating plasma for space engines, since the plasma of a high-frequency capacitive discharge has a low density (no higher than 10^{16} m^{-3}) at low pressure and low power, which will not be enough for efficient engine operation. For capacitive discharge plasma density data, see Chabert, R., & Braithwaite, N. (2011). Physics of radio-frequency plasmas. Cambridge University Press. The proposed antenna device, in particular the use of an inductively coupled coil in it, is impractical for use on board the small spacecraft. This is due to the fact that in this case, the energy from the inductor to the plasma will be transmitted as in a transformer, while the transformation ratio will not be higher than 0.5. Considering the power losses on the RF-generator-Inductor line and the antenna losses, to generate dense plasma (above 10^{18} m^{-3}), high power (above 800 W) will be required, making it impossible to use a motor with such a plasma source on small spacecraft, which have low power supply. The proposed antenna device, in particular the use of Double-Saddle and Loop antennas, is also impractical for use on board the small spacecraft. This is due to the fact that, as in the case with the use of capacitively coupled electrodes, at low powers, parasitic capacitive discharges will occur on the surface of the antenna itself and on the structural elements of the engine and small spacecraft. At the same time, with a long duration of these processes, due to the

sputtering of a metal antenna and metal elements of the engine structure, the outer surface of the gas discharge tube will be covered with a metal film that will absorb the electromagnetic radiation generated by the antenna and the process of ionization of the working medium inside the gas discharge chamber will be impossible, i.e. the engine will be damaged. The proposed location of the injector for gas injection into the gas-discharge chamber is ineffective from the point of view of power input into the plasma and ionization of the working fluid. When the working fluid is ionized at the beginning of the gas-discharge chamber and when an antenna is used in the ionizer that generates electromagnetic waves in the plasma (the Double-Saddle and Loop antennas proposed in the invention under consideration), more power will be spent on ionization and less power will be invested in the plasma, i.e. to the formation of waves in the plasma occurs behind the antenna, namely, the waves effectively ionize the gas and put power into the plasma. The use of a large number of magnetic systems is impractical because to accelerate the plasma, one magnetic nozzle at the exit from the gas-discharge chamber is sufficient. A large number of magnetic systems make the engine heavier and occupy a useful volume, which makes it unsuitable to use such an engine on board the small spacecraft. There is no electromagnetic shielding system in the invention. A device that uses electromagnetic waves and a magnetic field to generate and accelerate plasma generates electromagnetic radiation, which, when absorbed by the structural elements of the small spacecraft, can cause a magnetic moment that will begin to rotate the small spacecraft, as well as cause the target load of the spacecraft to malfunction or disable it.

Brief summary

The objectives of the invention are:

- elimination of shortcomings of analogues and prototype, namely:
- the occurrence of parasitic discharges that destroy the structural elements of the engine and small spacecraft;
- losses due to the contribution of power to the plasma on the antenna-plasma electromagnetic communication line;
- the influence of electromagnetic radiation on the structural elements of the propulsion system and the structural elements of the small spacecraft, leading to the rotation of the small spacecraft in space; and
- improvement of the following characteristics:

- reduction of the mass and volume occupied by the engine for cruising operations, correction and maintenance of the orbit of the small spacecraft, its orientation, maneuvers between orbits, withdrawal of the spacecraft at the end of its active life;

- increase in specific thrust and specific impulse of the engine per unit of power consumption.

To solve problems and achieve a technical result, a module with a plasma propulsion system for a small spacecraft is proposed, containing:

- elements of the rigid structure of the module, consisting of rods that make up a truss, which is a parallelepiped, to which structural elements and modules of the plasma propulsion system are attached, the edges of which are closed by elements of the electromagnetic shielding system, while on two edges of the truss of the propulsion system module there are at least two holes for the ends of the gas-discharge chambers, on three - at least one, one more face is free of holes for the ends of the gas-discharge chamber;

- at least three gas-discharge chambers made of dielectric material in the form of a cylinder with walls, the thickness of which can be of different designs, but such that there is a through cylindrical tract on the cylinder axis, located inside the module volume without intersecting, centered on the outer surface of each of which there is an antenna that generates an electromagnetic field inside the gas-discharge channel for ionization of the working medium, each end of the gas-discharge chambers is open to the external space, reaching the outer surface of the module as described in the previous paragraph, from each end of which there are magnetic systems, with each end hermetically connected to radial gas inlets, which are connected to each end of the gas discharge chamber to the location at each end of the gas discharge chambers of the magnetic systems;

- at least three antennas (according to the number of gas-discharge chambers), connected via communication lines with a module of RF generators, located centrally on the outer surface of each of the gas-discharge chambers, while on the outer side of the antenna they are covered with rings made of dielectric material;

- at least three rings made of dielectric material (according to the number of antennas), covering the antennas from their outer side from the rest of the plasma propulsion module;

- a storage and supply system of a propellant, consisting of at least one tank for storing the working fluid, at least six radial gas inlets, which are connected to the elements for supplying the working fluid;

- at least six radial gas inlets (for twice the number of gas-discharge chambers), which are hermetically connected to each of the ends of the gas-discharge chambers to the location of the

electromagnets of the magnetic systems on one side, each of which is connected to the working fluid supply elements;

- a RF generator module, consisting of at least three RF generators (according to the number of antennas) for independent regulation of the power supplied to the plasma in each gas-discharge chamber;

- at least three communication lines of RF generators with antennas (according to the number of antennas), which electrically connect RF generators with antennas;

- at least six magnetic systems (for twice the number of gas-discharge chambers), which are located at each of the two ends of the gas-discharge chambers, consisting of electromagnets connected to the power sources of the electromagnets, while the electromagnets create an axial one, coinciding with the axis of the corresponding gas-discharge chamber, and perpendicular to the center line the corresponding gas-discharge chamber, magnetic fields at the ends of each gas-discharge chamber, accelerating the plasma generated in the gas-discharge chambers using four mechanisms - electrostatic, electromagnetic, gas-dynamic, Joule heating;

- onboard power conversion module, electrically connected to onboard power supplies on board a small spacecraft, RF generators module, magnetic system power supplies;

- a control module that sets control actions on the on-board power conversion system, the storage and supply system of the working fluid, the RF generator module, the magnetic system power supplies, the multichannel plasma propulsion system module that collects information on the characteristics of the systems, and transmits this information to the small spacecraft for its further transfer to the command post;

- an electromagnetic shielding system, consisting of thin elements of a material that shields electromagnetic and magnetic radiation.

The module with a multichannel plasma propulsion system for small spacecraft is proposed to be used on small spacecraft for their prior to launching from the reference orbit to the target orbit, correcting and maintaining the orbit, precision orientation, unloading the attitude control systems, maneuvers between orbits, and removing the small spacecraft from the target orbit at the end of its active life.

Brief description of drawings

FIG. 1 shows a structural block diagram of the proposed module with a multichannel plasma propulsion system for small spacecraft.

Detailed description

- elements of the rigid structure of the module (1), which perform the function of maintaining the components of a multichannel plasma propulsion system, such as gas-discharge chambers (2), a system for storing and supplying a working fluid (3), a module of RF generators (4), magnetic systems (5), onboard power conversion module (6), control module (7), electromagnetic shielding system (8). The elements of the rigid structure of the module (1) are rigidly connected to the small spacecraft. The elements of the rigid structure of the module (1) perceive the traction forces transmitted to the elements of the module (1) from the magnetic systems (5), to which the traction forces are transmitted from the plasma leaving the gas-discharge chambers (2) along the lines of axial magnetic fields generated by the magnetic systems (5) ... The elements of the rigid structure of the module (1) transmit the traction forces they perceive to the body of the small spacecraft through the rigid connection between the elements of the module (1) and the body of the small spacecraft, thereby setting it in motion in outer space;

- at least three gas-discharge chambers (2) rigidly connected to the elements of the rigid structure of the module (1). Antennas (9) are fixed in the center on the outer surface of each of the gas-discharge chambers (2). At each end of each gas discharge chamber (2) there are two electromagnets of magnetic systems (5) - an electromagnet (10), which creates an axial one that coincides with the axis of the corresponding gas discharge chamber (2), and an electromagnet (11), which creates a perpendicular to the axis of the corresponding gas discharge chamber (2) magnetic fields. Gas discharge chambers (2) are channels where plasma is generated. The axes of the gas-discharge chambers (2) coincide with the axes of the control actions on the small spacecraft, i.e. the axes of the gas-discharge chambers (2) coincide with the vectors of the thrust forces created by the accelerated plasma flows leaving the gas-discharge chambers (2). From each gas discharge chamber (2), the accelerated plasma flow can exit in two directions, i.e. each gas discharge chamber (2) has two thrust vectors having a common axis, which is the axis of the corresponding gas discharge chamber (2), but opposite in direction. At each end of the gas discharge chamber (2) to the location of the electromagnets (10) and (11) of the magnetic system (5), there is a place of hermetic connection with radial gas inlets (12), each of which is hermetically connected to the storage and supply system of the working fluid (3) ;

- at least three antennas (by the number of gas-discharge chambers) (9), electrically connected to at least three communication lines of RF generators with antennas (13), respectively, i.e. each antenna (9) is connected to one communication line of the RF generator with the antenna (13), which are connected to one of the RF generators (14) located in the module of the RF generators (4). Antennas (9) are located centrally on the outer surface of each of the gas discharge chambers

(2), respectively, i.e. each gas-discharge chamber (2) corresponds to one antenna (9). The antennas (9) are fed HF power through the communication lines of RF generators with antennas (13) from RF generators (14) located in the module from RF generators (4), which is converted by antennas (9) into an alternating electromagnetic field inside the gas discharge chambers (2). Variable electromagnetic fields generated by antennas (9) inside the gas-discharge chambers (2) cause oscillations of the electrons of the working fluid introduced into the gas-discharge chambers (2) by radial gas inlets (12). Oscillations of the electrons of the working medium inside the gas-discharge chambers (2) cause avalanche ionization of the working medium, i.e. the process of plasma formation occurs inside the gas-discharge chambers (2). In the presence of an axial magnetic field created by electromagnets (10) of the magnetic system (5), the electromagnetic fields generated by the antennas (9) cause the formation of their own electromagnetic waves in the plasma, in particular, helicon waves, which, in turn, create Trivelpiece-Gould waves or oblique Langmuir waves, which increase the degree of plasma ionization inside the gas-discharge channels (2) and effectively invest the power transmitted by the antennas (9) into the plasma inside the gas-discharge chambers (2). On the outer surface of each of the antennas (9), rings made of dielectric material (15) are fixed;

- at least three rings of dielectric material (15) (according to the number of antennas), fixed on the outer surface of each of the antennas (9), i.e. each antenna (9) corresponds to one ring of dielectric material (15). Rings made of dielectric material (15) prevent the propagation of electromagnetic radiation generated by the antennas (9) into the volume of the module of the multichannel plasma propulsion system. Dielectric rings (15) prevent the formation of parasitic capacitive discharges on the surface of the antenna (9), on the structural elements of the engine module;

- storage and supply systems for the working fluid (3), including at least one tank for storing the working fluid (16), at least six radial gas inlets (12), which are hermetically connected to the working fluid supply elements (17) of the working fluid storage and supply system (3), which have a tight connection with at least one tank for storing the working fluid (16). The storage and supply system of the working medium (3) is rigidly fixed on the elements of the rigid structure of the module (1). The working fluid storage and supply system (3) serves to store the working fluid in the tank (16), prepare and regulate the working fluid flow rate in the working fluid supply elements (17), enter the working fluid into the gas-discharge chambers (2) using radial gas inlets (12);

- at least six radial gas inlets (12) (twice the number of gas discharge chambers), which are hermetically connected to each of the ends of the gas discharge chambers (2) to the location of

the electromagnets (10) and (11) of the magnetic systems (5), each of which is hermetically connected with elements for supplying the working fluid (17);

- a module of RF generators (4), consisting of at least three RF generators (14) (according to the number of antennas). The module of RF generators (4) contains at least three RF generators (14) to provide independent regulation of the power deposited into the plasma in each gas discharge chamber (2) using antennas (9). Independent regulation of the power supplied by the antennas (9) to the plasma in each of the gas-discharge chambers (2) is necessary in order to control the direction of the main thrust vector, which is the sum of the thrust vectors F_T corresponding to the axes and directions of the plasma exit from the gas-discharge chambers (2);

- at least three communication lines of RF generators with antennas (13) (according to the number of antennas), which electrically connect the RF generators (14) of the module from HF generators (4) with antennas (9);

- at least six magnetic systems (5) (for twice the number of gas discharge chambers), which are located at each of the two ends of the gas discharge chambers (2), consisting of electromagnets (10) and (11), electrically connected to the power sources of the electromagnets (18), the electromagnets (10) create an axial magnetic field coinciding with the axis of the corresponding gas discharge chamber (2), and the electromagnets (11) create a magnetic field perpendicular to the axial line of the corresponding gas discharge chamber (2). Electromagnets (10) are located closer to the cuts of the gas discharge chambers (2), electromagnets (11) are located next to the electromagnets (10) on the side that is farther from the cuts of the gas discharge chambers (2). Electromagnets (10) located near the cut of each gas discharge chamber (2), creating an axial magnetic field parallel to the axis of the corresponding gas discharge chamber (2), accelerate the plasma generated in the gas discharge chambers (2) using four plasma acceleration mechanisms - electrostatic, electromagnetic, gas-dynamic, Joule heating. Electromagnets (11), creating a magnetic field transverse to the axial line of the corresponding gas discharge chamber (2), serve as plasma filters, i.e. regulate the plasma mass flow rate, which, when passing the transverse axis of the corresponding gas discharge chamber (2) of the magnetic field, can be accelerated by means of an axial parallel to the axis of the corresponding gas discharge chamber (2), the magnetic field created by electromagnets (10) on each of the cuts of the gas discharge chambers (2). Thus, electromagnets (11) play the role of plasma filters in order to reduce the amount of plasma flowing out in one of two possible directions of each of the gas-discharge chambers (2) or prohibit plasma outflow in these directions, i.e. using electromagnets

(11), it is possible to control both local (in each of the two possible directions of each gas-discharge chamber (2)) thrust vectors, and the main thrust vector, which is the sum of local ones;

- onboard power conversion module (6), electrically connected to onboard power sources on board a small spacecraft, RF generators module (4), working fluid storage and supply system (3), magnetic system power supplies (18), control module (7). The onboard power conversion module (6) converts the electric current coming from the onboard power sources on board the small spacecraft to the modules and systems of the module with a multichannel plasma propulsion system necessary for operation;

- the control module (7), which sets the control actions on the onboard power conversion system (6), the RF generator module (4), the magnetic system power supplies (18), which collects information on the characteristics of the modules and systems of the module with a multichannel plasma propulsion system, transmitting this information to the board of the small spacecraft for its further transmission to the command post, receiving information about control actions that were sent to the board of the small spacecraft from the command post;

- an electromagnetic shielding system (8), consisting of thin elements that absorb electromagnetic radiation. Thin elements of the electromagnetic shielding system (8) cover the outer surface of the module with a multichannel plasma propulsion system for a small spacecraft. The electromagnetic shielding system is used to eliminate the effect of electromagnetic radiation and magnetic fields of the module with a multichannel plasma propulsion system on structural elements, systems and modules of a small spacecraft.

The main task performed by the module with a multichannel plasma propulsion system for a small spacecraft is to create 6 thrust vectors located in different projections to create a total thrust vector performing control actions, i.e. before launching the small spacecraft from the reference orbit into the target orbit, correcting and maintaining the orbit, precision orientation, unloading the attitude control systems, maneuvers between the orbits, removing the spacecraft from the target orbit at the end of its active life.

In promising developments in the field of electric rocket engines, they came to the use of a magnetic nozzle to control the plasma flow. EJE's using magnetic nozzles are classified as electromagnetic and include magnetoplasmodynamic, helicon and VASIMR motors. These advanced engines are required to meet the requirements of future space missions and are designed to produce high specific impulse and thrust more than existing ERE at the same power level.

Magnetic nozzles, presented in the invention by electromagnets (10), like Laval nozzles, convert the thermal energy of the particles of the working fluid or their randomly directed kinetic energy into directed kinetic energy. The advantage of magnetic nozzles is that the contact of the

high-temperature plasma with the nozzle surface is minimized, while magnetic nozzles provide the possibility of using additional mechanisms for generating thrust due to the interaction of plasma and their magnetic fields.

The power contribution to the plasma, the separation of the plasma from the magnetic lines and the transmission of the accelerated plasma pulse in the electromagnetic field created by the antenna (9) along the lines of the magnetic field created by the electromagnets (10) of the magnetic systems (5) are important steps for generating thrust in the magnetic nozzle. The mechanisms by which kinetic energy is extracted from the plasma using electromagnets (10) magnetic systems (5) to create traction forces include the law of conservation of the adiabatic invariant of the magnetic moment, electric field strength, direction of thermal energy, and Joule heating. Plasma detachment mechanisms include resistive diffusion of a magnetic field, recombination processes in plasma, magnetic reconnection of magnetic field lines, loss of adiabaticity of the plasma expansion process, effects of inertial forces, and effects of stratification of lines of intrinsic electromagnetic fields. The process of impulse transfer from the plasma to the spacecraft is a consequence of the interaction between the lines of the applied magnetic field created by electromagnets (10) and the induced fluxes that are formed due to magnetic pressure.

Three key steps are required to generate thrust in the magnetic nozzle:

- Conversion of magnetoplasma energy into directed kinetic energy;
- Effective separation of plasma from magnetic field lines;
- Transfer of angular momentum from plasma to spacecraft.

The main mechanisms of energy conversion in a magnetic nozzle and the corresponding types of acceleration between which energy is transferred are presented below:

- Conservation of the adiabatic invariant of the magnetic moment (acceleration in an electromagnetic field);
- Acceleration in an electric field;
- Direction of motion of thermally heated particles (gas-dynamic acceleration);
- Joule heating (thermal acceleration).

Conservation of the adiabatic invariant of the magnetic moment.

The magnetic moment of a particle is adiabatically constant during motion if the change in the magnetic field during one period of cyclotron motion is many times less than the value of the magnetic field induction. The adiabatic conditions can be represented by various dependencies. The most frequently used condition is determined by the ratio of the Larmor radius of a particle $r_L = mv_{\perp}/(qB)$ to the characteristic size of the change in the magnetic field defined as $1/|gradB|$:

$$r_L |grad B| \ll 1.$$

To further describe the adiabatic energy exchange, we put a simplified energy expression for isentropic, collisionless, and equipotential plasmas in the following form:

$$K_{\Sigma} = K_{\perp} + K_{||} = \frac{mv_{\perp}^2}{2} + \frac{v_{||}^2}{2} = const.$$

From these conservation equations it is seen that a decrease in the magnetic field strength leads to an increase in the particle velocity parallel to the magnetic field. This behavior is similar to the familiar physics of a magnetic mirror. Combining these equations leads to the following relationship for the velocity parallel to the magnetic field:

$$v_{||} = \sqrt{v_{\Sigma}^2 - 2\mu_m B/m}.$$

Additional insight can be gained by assuming that a flow initially dominated by the perpendicular velocity component gradually flows into an area with a very small magnetic field. The expression for the output velocity for this flux is shown below and is an expression for the total energy conversion associated with a magnetic moment parallel to kinetic energy:

$$v_{||,max} = \sqrt{2\mu_m B_0/m}.$$

Acceleration by electrostatic field.

Electrostatic acceleration can be caused by the formation of ambipolar fields or double layers. These mechanisms are the result of the high mobility of electrons as compared to ions. This increased mobility is characterized by thermal velocity. In expanding magnetic nozzles, mobile electrons form an electron pressure gradient in front of slow ions. To maintain quasi-neutrality, an electric field is formed, which accelerates ions and slows down electrons. This leads to an exchange of energy between the thermal velocity of electrons and the velocity of the ion flow.

Although ambipolar acceleration and acceleration in a double layer are due to similar physics, they are completely different. Double layers are characterized by a change in potential in the region of several Debye lengths, while the measurement of the potential in the ambipolar mechanism can be of the order of the characteristic dimensions of the system.

Direction of movement of thermally heated particles.

Kinetic energy can be obtained by directing thermal energy. Laval nozzles direct thermal motion in an axial direction through a converging-diverging physical wall. Magnetic nozzles do this by confining the plasma to the desired geometric shape using a strong guiding field. The physics of energy conversion is based on hydrodynamics, and the geometry of the magnetic nozzle is determined by the interaction of the plasma with the magnetic field. This implies that relationships based on hydrodynamics, similar to those used in the analysis of Laval nozzles, can

be used to analyze this energy conversion, neglecting the losses resulting from the formation of the magnetic wall.

The main condition of plasma confinement in relation to thermal forces is characterized by the ratio of the pressure of the continuous medium to the magnetic pressure, presented in the following expression:

$$\beta_p = \frac{nk_B T}{B^2/2\mu_0}.$$

If this ratio is satisfied, i.e. the magnetic pressure is stronger than the thermal pressure, then plasma confinement is possible but not guaranteed. Plasma confinement may also require the formation of a current sheet at the plasma-vacuum interface. Diffusion and convection processes can degrade the current sheet, so they must be understood in order to prevent losses caused by non-ideal plasma confinement.

Joule heating.

Energy exchange can also arise from the interaction of electromagnetic and hydrodynamic fields. This exchange is best described by the magnetohydrodynamics energy equation given below:

$$\frac{\delta e_H}{\delta t} + \nabla \cdot [U(e_H + p) - k\nabla T + U \cdot \tau] = \mathbf{J} \cdot \mathbf{E}.$$

The right side of the expression presented above is the expression for heating according to the Joule-Lenz law and describes the energy received by a continuous medium due to the loss of energy by an electromagnetic field. The same part of the expression, only with the opposite sign, is presented in the equation for the energy of the electromagnetic field:

$$\frac{1}{2} \frac{\delta}{\delta t} \left(\varepsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0} \mathbf{B}^2 \right) + \nabla \cdot \left[\frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \right] = -\mathbf{J} \cdot \mathbf{E}.$$

Plasma detachment.

In order for the magnetic nozzle to create thrust, the directed kinetic energy must be disconnected from the lines of the applied field. Plasma decoupling mechanisms have become a major consideration in the design of a magnetic nozzle in an attempt to minimize losses associated with electromagnetic resistance forces and plasma divergence. Plasma disconnection mechanisms should be divided into three categories: collisional, collisionless, and magnetic line reconnection disconnection.

Collisional separation. Collisional separation can be achieved by means of Bohm diffusion across the magnetic field lines and recombination of ions and electrons.

Bohm diffusion. It is assumed that Bohm diffusion is a factor in achieving detachment and is determined by the diffusion of plasma across the magnetic field lines. Bohm diffusion presents conflicting requirements for the initial bonding required for correct nozzle geometry and the final

transverse diffusion field required for decoupling. The resistivity must also be reduced. It is assumed that a gradually diverging magnetic field is more suitable for providing Bohm plasma separation.

The magnetic Reynolds number is used to quantify the binding of plasma in a magnetic nozzle. For larger values, Boom detachment is neglected compared to convection effects and bonding is achieved. For intermediate values, diffusion is important and the plasma can move across the magnetic field lines. Therefore, large values of the magnetic Reynolds number are required for bonding, while intermediate and small values are required for separation. It is important to note that although the magnetic Reynolds number provides insight into the diffusion regime, quantitative comparisons should be made with caution due to the ambiguity in the choice of the linear scale. Magnetic Reynolds numbers are best used for qualitative comparison and can be used for quantitative comparison for systems that are physically and geometrically similar.

A method for predicting the magnitude at which a plasma will diffuse through a magnetic barrier has been studied and suggests that the plasma may exhibit anomalous resistivity that is several orders of magnitude greater than that predicted by classical plasma theory and Bohm's diffusion. The existence of anomalous resistivity, therefore, must be considered numerically. As a means of providing resistive separation, Bohm diffusion was considered to a greater extent as ineffective due to side effects that would affect the process of generating thrust, as well as divergent diffusion that might take place. Nevertheless, resistive effects cannot be neglected, since they can be important in experiments. Plasma separation in the far region from the exit of the magnetic nozzle due to resistive effects may be of interest, in particular, in the region close to the nozzle axis, where the time of flight of bound particles can be longer than the times between collisions.

Recombination processes. Particle recombination processes implement plasma detachment due to the formation of neutral particles, which are no longer subject to the influence of magnetic fields. The process of formation of neutrals is primarily a consequence of the recombination of three particles, in which two of them of the same sign interact with the other of the opposite sign, forming a neutral and a high-energy particle. The recombination process requires the presence of an ion-electron collision frequency at a sufficiently high level that will ensure effective separation. Although the initial consideration of the recombination process as a means of achieving separation is not encouraging, the recombination frequency can be increased by the configuration of a sharply decreasing magnetic field or the rapid cooling of electrons in an expanding nozzle.

Collisionless separation. The main means for achieving collisionless separation are the loss of adiabaticity, the effects of electron inertia, and the effects of the induced magnetic field.

Loss of adiabaticity. Detachment due to the loss of adiabaticity occurs when the conditions for adiabatic expansion of plasma in a diverging magnetic field are violated and the plasma, as a result, becomes demagnetized. Plasma demagnetization implies that the particles are no longer subject to the effects that cause them to rotate around a single line of the magnetic field. Such a regime can be best demonstrated by representing a particle that begins to rotate around one magnetic field line, and then, during its rotation, crosses a completely different magnetic field line, while changing the orbit of motion.

The loss of adiabaticity is inherent in both ions and electrons, but to a greater extent for ions than for electrons, since demagnetization of ions is more likely due to their much larger Larmor radius compared to the electron one. It is theoretically assumed that the loss of adiabaticity of only ions does not guarantee separation due to the formation of electric fields between bound electrons and outflowing separated ions. Detachment in this particular complex case refers to the inertial detachment of individual plasma particles and will be discussed in the next section. The loss of adiabaticity describes the process of detachment of individual plasma particles; however, the detachment of the entire outflowing plasma is guaranteed only in the case when both ions and electrons are demagnetized. The separation due to the loss of adiabaticity can also be studied with the help of a more complex Lagrangian invariant, which determines the individual regions in which charged particles can be found.

Inertial separation. As mentioned in the previous section, in the case of inertial separation, the case is considered when only particles of the same type are demagnetized and an electric field is formed that maintains the quasi-neutrality of the plasma flow leaving the nozzle. However, plasma detachment can still be achieved by particles that have sufficient inertia to overcome the binding magnetic field forces. A hybrid Larmor radius based on a hybrid particle mass was introduced to simplify the study of this model. Detachment in this case can be considered as a drift of hybrid electron-ion particles. The ratio of the magnetic inertia to the inertia of the plasma flow is described by a dimensionless quantity represented in the following expression:

$$G \approx \frac{eB_z}{m_e} \frac{eB_z}{M_i} \frac{r_0^2}{u_0^2}.$$

Significant theoretical and numerical contributions were made to the study of the efficiency of the inertial separation process, with one group of researchers believed that demagnetization based on the hybrid Larmor radius was an effective means for separation, while others believed that only when demagnetizing electrons could separation effectively be achieved plasma.

Inertial pull-off is often referred to as a lower pull-off limit that can be enhanced by other mechanisms.

Separation due to the induced fields. Plasma separation due to induced magnetic fields is possible either by lengthening the magnetic field to infinity, or by neutralizing the external applied magnetic field and thus demagnetizing the plasma. The separation efficiency due to induced fields can be studied by considering the currents that these fields created.

The lengthening of the magnetic field occurs when the kinetic energy of the plasma exceeds the magnetic energy, or in other words, when the gas-dynamic velocity of the plasma exceeds the Alfven velocity. The elongation of the magnetic field is characterized by a dimensionless parameter presented in the following expression:

$$\beta_f = \frac{\rho u^2/2}{(B^2/2\mu_0)} > 1.$$

When this inequality is satisfied, the plasma is considered superalfvend and moves faster than the speed with which changes in the magnetic field affect the flow. As a result, the lines of the magnetic field are lengthened to infinity due to friction forces, remaining as if frozen into the plasma flow. The currents required for the superalfven separation regime are paramagnetic, which results in converging separation, but increases the thrust losses due to the forces of attraction between the applied field and the field of the induced currents. Theoretical studies have shown that the transitional regime between the pre-Alfvén flow and the superalfvén flow can minimize losses during plasma separation, since the magnetic field will diverge slowly. In experimental studies, it was assumed that the separation mode due to the lengthening of the magnetic field is more probable than demagnetization of ions, and the experimental results agree with the results of numerical simulation. However, the elongation of the magnetic lines cannot be measured. The results of other experimental studies and computer simulations also showed superalfven separation and determined the mechanism of self-collimation of the plasma flow.

The neutralization of an external applied magnetic field by means of an induced field refers to the process of self-demagnetization and occurs due to the formation of diamagnetic currents in the plasma. These currents create an axial accelerating force. Diamagnetic currents, which facilitate separation, are beneficial due to the transfer of momentum to the spacecraft, but they create a diverging plasma jet. The configuration of the magnetic field lines to achieve this type of separation is similar to the one that will be considered in the case of separation during magnetic reconnection. Detachment during self-demagnetization was shown by the method of computer simulation.

Reconnection of magnetic field lines. The problem of reconnecting magnetic field lines is widely studied in plasma physics, but until now this problem has been insufficiently studied in

relation to the problem of plasma separation to create thrust. The manifestation of plasma detachment due to magnetic reconnection is noticed in coronal mass ejections on the Sun and magnetic binding in thermonuclear experiments.

In Shumeiko, A. I., and Telekh, V. D. Probe diagnostics of the plasma plume created by a magnetic nozzle of an inductively coupled plasma source. In *Journal of Physics: Conference Series*, Vol. 1393, No. 1, p. 012027 (<https://doi.org/10.1088/1742-6596/1393/1/012027>) shows the results of measuring the plasma flow velocity at the exit from a magnetic nozzle (in the invention of electromagnets (10)), accelerated by electrostatic plasma acceleration, i.e. formation of a double electrostatic layer in the plasma flow at the exit from the magnetic nozzle.

In this work, a laboratory model, ABHPT, of an ERE with a helicon plasma source and a magnetic nozzle. The engine consisted of a discharge chamber (in the invention a gas discharge chamber (2)) of quartz glass with a closed end, a wall thickness of 3 mm, an inner diameter of 50 mm, and a length of 200 mm. At the open end of the discharge chamber, there was a membrane with a hole 20 mm in diameter, which served to form a collimated plasma flow.

A helicon antenna (antenna (9) in the invention), 12 cm long, made of copper, surrounded the gas-discharge chamber and was attached to one of the flanges of the vacuum chamber. The antenna was positioned a few millimeters from the gas discharge chamber to minimize capacitive coupling and reduce thermal effects. Electromagnets (in the invention, electromagnets (10)) created a diverging magnetic field with a maximum magnetic field of 200 G.

The ABHPT was installed inside a vacuum chamber 0.7 m in diameter and 1 m in length. The chamber was made of non-magnetic stainless steel, which is resistant to deformation caused by thermal cycles, high vacuum and degassing, to simulate vacuum conditions in low Earth orbit (LEO), in which pressure is usually less than 10^{-2} Pa. The vacuum chamber had a turbomolecular/rotary pumping system that maintained a base pressure of less than 10^{-3} Pa, and the effective pumping rate measured for air was approximately $300 \text{ l}\cdot\text{s}^{-1}$. At such pressures, the thermal environment of outer space can be simulated, since the thermal conductivity of gases is low compared to radiant heat transfer. The pressure in the chamber was measured using an MKS 220CA Baratron device, which was located on one of the flanges of the vacuum chamber.

Four flanges of the vacuum chamber provided the supply of the working fluid supply lines, electric power supply for electromagnets, high-frequency current for the antenna, and power supply of the plasma diagnostics system circuit. The working fluid (air) was supplied to the gas discharge chamber using a polyamide tube attached to its closed end, and its flow rate was

controlled by a mass flow controller installed outside the vacuum chamber. The mass flow controller MKS Ture 2160 V was used as a flow regulator.

The load/generator RF matching devices outside the vacuum chamber were connected to the ABHPT antenna with an RG-213 coaxial cable and two copper rods enclosed in a copper shield. High frequency power (13.56 MHz) was maintained at 120 watts to reduce the thermal load on the ABHPT. For the same reasons, the current applied to each solenoid was limited to 2A to avoid overheating and melting of the solenoid copper wire.

To confirm the characteristics of the ABHPT required to support the aforementioned small spacecraft in an orbit of 200 km, the ion energy distribution function and the local plasma potential were measured by both the ion energy analyzer (IEA) and the Langmuir probe, respectively.

IEA was installed on the center line of the ABHPT and the vacuum chamber. IEA consisted of three grids and a collector plate. Plasma particles entered the analyzer through a 5 mm hole in a 0.1 mm thick stainless steel plate. The perforated plate was in electrical contact with the analyzer body, which was connected to a grounded vacuum chamber. The analyzer grid voltages were set at -90, -20 and -10 V. The measured current was the sum of the collector current and the secondary grid current, which corresponds to any secondary electrons emitted from the collector plate when exposed to ions. For this purpose, the offset of the secondary grid was set at -20 V. The analyzer was used only in the ion collection mode. The voltage on the discriminator grid was varied from 0 to -150 V with a step of 0.5 V, and 100 current measurements were averaged for each measurement step.

The Langmuir probe was mounted on the AVHRT centerline. The bias voltage was varied from -150 V to 150 V in 0.5 V steps, with 100 current measurements averaged per step to obtain a time-averaged I-V curve. The local plasma potential was determined by the derivative of the I-V curve.

The characteristics of the plasma and plasma flow, created by AVHRT, were investigated at a working fluid flow rate of $1.5 \text{ mg}\cdot\text{s}^{-1}$, a pressure of 50 mP, a magnetic field of 200 Gs, and an RF power of 120 W. The local plasma potential V_{local} , measured by the Langmuir probe, corresponded to the location of the greatest magnetic field gradient and in this position was 60 V relative to the chamber. The measured ion energy at this point was 80 V. In this case, the velocity of the plasma flow emerging from the magnetic nozzle (in the invention of electromagnets (10)) was $11 \text{ km}\cdot\text{s}^{-1}$.

This study demonstrated the experimental results of testing ABHPT in LEO conditions. These results show that a motor with a magnetic nozzle (in the invention of electromagnets (10)) can

successfully support SSC in LEO. It is shown that ions generated in a wave (helicon) plasma source can be accelerated in an ABHPT by a magnetic nozzle using the electrostatic acceleration mechanism provided by a forming double electrostatic layer at the exit from the magnetic nozzle, up to speeds of $11 \text{ km}\cdot\text{s}^{-1}$ at a power of 120 W. The engine created a thrust of 18 mN.

Claims

1. A module with a plasma propulsion system for small spacecraft, containing a gas-discharge chamber that determines the axis of thrust forces, an antenna, magnetic systems, ***characterized in that*** the module contains at least three gas-discharge chambers, the axes of which are directed at least in three different directions in space, each of two ends of which is open to the external atmosphere, each of which defines two thrust vectors located on an axis coinciding with the axis of the corresponding gas discharge chamber, directed in opposite directions, contains at least three antennas, one for each gas discharge chamber, located centrally on the outside of each gas discharge chambers, surrounded on the outside by at least three rings of dielectric material, one for each antenna, contains a module of RF generators, consisting of at least three RF generators, each of which is electrically connected to one of the antennas, respectively, contains a minimum of six magnetic systems, one by one at each end of the gas discharge chambers, each of which consists of two electromagnets: the first electromagnet creating a magnetic field transverse to the axis of the corresponding gas discharge chamber, located farther from the end of the corresponding end of the corresponding gas discharge chamber than the second electromagnet, creating an axial parallel to the axis of the corresponding gas discharge chamber magnetic field, electromagnets are connected to the power supply system of magnetic systems, contains a storage and supply system of a propellant connected to the gas discharge chambers using at least six radial gas inlets, hermetically connected to the gas discharge chambers in two places located to the locations of the magnetic systems, contains an onboard power conversion module, electrically connected to the module of RF generators, the power supply system of magnetic systems, the storage and supply system of a propellant, contains a control module, contains the elements of the rigid structure of the module that make up a parallelepiped, rigidly connected to the gas-discharge chambers, the storage and supply system of a propellant, the module of RF generators, magnetic systems, the module for converting the onboard power supply, the control module, contains an electromagnetic shielding system consisting of thin elements absorbing electromagnetic radiation, having a rigid connection with the elements of the rigid structure of the module.