EXPENDING PLASMA JET FROM THE NOZZLE OF THE RF-PLASMA THRUSTER

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The concept of the thermoelectric thruster with high-frequency heating of working substance is suggested in this article. It enables to reduce essentially the plasma influence on elements of the plasma thruster, to eliminate energy losses on electrodes and in the nozzle of the thruster for increase of the thruster efficiency and the operating time. The free expansion of ideal non-equilibrium plasma -jets from the nozzle of RF-plasma thruster is considered. The outflow medium consists of ions, electrons and neutrals (atoms and molecules). The non-stationary plasma -dynamics equations are used for the numerical simulation. The solution is provided by the determination method with modify finite-difference Godunov´s scheme based on the mobile grid. The model calculations of the axially symmetric outflow of the mono velocity three-componential plasma of two temperature levels from the round nozzle of the RF-plasma thruster into the vacuum are carried out.

Nomenclature

c_p, c_v – specific thermal capacity values at a constant presure and a constant volume;
e – specific internal energy;
e-electron charge;
h – specific enthalpy;
I – ionization energy;
k – Boltzman's constant;
M – Mach number;
m – mass of a particle;
n – volumetric density (concentration) of particles;
p – pressure:
R – universal gas constant;
r – radius;
T – temperature;
t – time;
v -velocity vector;
u_x, u_y, u_z – velocity vector components on the axes x,y,z;
a – ionization degree;
$g = c_p / c_v$ – specific thermal capacity values ratio
r – density;
s – cross-section of collisions. Stephan-Boltzman's constant

Introduction

Power engineering of space vehicle with the lifetime in the range from one to 20 years will always be an urgent problem. Thrusters, which perform correction and stabilization of such space vehicles, have their own peculiarities such as long time of operation, high reliability, optimal "relative" thrust and specific gravity. Long-terminal resource needs a moderate temperature of construction parts of plasma thrusters, and the plasma flow would not interact with these parts. Mainly the velocity of plasma exhausting (specific pulse) determines "relative" thrust of plasma thruster. It is clear that the higher the specific pulse the greater the "relative" thrust is.

To perform extended space works it is necessary to have thrusters with velocities of plasma exhausting from 1000 m/s to 10^5m/s. For velocities of working substance exhausting from 1000 m/s to 9000 m/s thermoelectric thrusters operate reliably, whereas few thrusters with exhausting velocities ranged from 2000 to 20000 m/s are available at present[1–3]. The use of electric arc plasma thrusters (arcjets) for these purposes demonstrates that in this velocity range negative phenomena appear effecting the resource of thrusters. Increasing of the plasma temperature in such thrusters leads to increasing of the "relative" thrust. But almost 50% of electrical power goes into the electrode heating and increasing influence of the plasma flow on the parts of thruster and reducing their resource[3–4].

One of the modern directions in the development of plasma accelerators is to design the thruster operating on principles of electrodeless pumping of electromagnetic power in the form of HF- and SHF-fields into plasma volume, plasma confinement and accelerating in the configured magnetic field. In this case the conception of thermoelectric thrust with RF-heating of the working substance such as hydrogen is proposed as well. This permits to minimize essentially the influence of plasma on elements of the accelerator to exclude the energy consumption on the electrodes[2–4], and the use of the magnetic nozzle significantly increases the efficiency of thrusters.

The advantages of this type of thrusters are the following:

-High efficiency;
-Enhanced resource of continuous operation aboard;
-High reliability and safety;
-Using of the ecological fuel;
-Providing the specific pulse in the required range of exhausting velocities;
-Weight characteristics, "relative" thrust and overall cost of installation will not exceed those existing at present.

The hydrogen application as a working substance has a number of advantages.

-Since hydrogen has minimum atomic mass the plasma exhausting velocity would be maximum compared with other working substances.
-Hydrogen is the ecological working substance.
-It is well-known that the energy transmission from an electron to a hydrogen ion is maximum because of minimum mass differences.
-At present the technology is developed for safe storing of bounded hydrogen aboard of a space vehicle due to the use of hydrides of metals and nano-tubes. .

Simulation of an expending plasma jet from the nozzle

The reached steady state of a supersonic outflow of an ideal non-equilibrium plasma jet into vacuum was an essence of investigation of various authors[5,6,7,13,17]. The initial conditions of the problem are the parameters on the edge of the nozzle. In a case of the perfect gas[10–14] the jet outflow is uniquely defined by assigning the Mach number, the inclination angle of the velocity vector to the symmetry axis and the value g on the edge of the profiles. Outflow of the perfect gas corresponds to the outflow of entirely freeze plasma into vacuum and may be considered as the certain limiting case of free expending of non-equilibrium plasma. There is no analytical solution of the problem of such a formulation even for the perfect gas. Available precise solutions are gained due to the methods of numerical simulation[10,16]. The detail description of both precise and approximate calculation methods of free expending of the ideal perfect gas is available. The analysis of results of the numerical investigation is contained in transactions[11,12]. The methods developed for the perfect gas in various cases may serve as the fundamental to solve the problems of plasma expending. Although, in a general case free expending of non-equilibrium plasma differs by a number of considerable features.

In a general case the equations expressing the laws of conservation of mass, impulse and energy of the system containing the substance and irradiation (non-equilibrium in a general case) are given in[12,13]. These equations form the system of equations, which present plasma motion taking into consideration energy, pressure of irradiation and radiant heat transfer.

As it is mentioned[13], the pressure and density of the irradiation energy are small comparatively to the gas-dynamic pressure and the internal plasma energy for relatively low-temperature plasma, which is typical for the majority of application areas. Only radiant heat transfer is considerable as usual. Since maximum ratio of the inflow velocity of the radiant energy to convectional transfer velocity has been $\sigma T^4/(\rho\upsilon\eta) << 1$, the problems of calculation of gas-dynamic flow parameters may be separated and solved independently one from another. The simplest models of the irradiation plasma are the models of optically absolute thick and thin media. As for the influence of energy losses at the expense of irradiation on plasma dynamics these models may be considered as limiting cases. There are no energy losses at the expense of irradiation in optically absolute thick plasma. These kinds of energy losses in optically absolute thin plasma are uniquely defined by the local plasma parameters. These models are applied in the cases when gas-dynamical plasma parameters (not the flow parameters) are of the main interest.

It's possible to use simple hydro-dynamical models solving the majority of practical problems of applied plasma dynamics. The theory of supersonic plasma jets is mainly based on the model of the hydro-dynamically ideal (non-viscous and non heat-conductive) plasma, which shows the flow in nozzles and jets rather satisfactory[13]. One can consider the approximation of the optically absolute thick plasma. When there are no electrical and magnetic fields, the hydro-dynamical equations including the continuity equations (three in a general case) of motion, energy and state may be written in a form [12].

For each of A plasma component:

$$\frac{\partial \rho_\alpha}{\partial t} + \sum_{i=1}^{3} \frac{\partial}{\partial x^i} \rho_\alpha \upsilon_\alpha^i = \zeta_\alpha \tag{1}$$

$$\frac{\partial \rho_\alpha \upsilon_{\alpha i}^i}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(\rho_\alpha \upsilon_\alpha^i \upsilon_\alpha^j + p\delta^{i,j} \right) = p_\alpha^i , \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho_\alpha e_\alpha + \frac{\rho_\alpha \upsilon_\alpha^2}{2} \right) + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left[\rho_\alpha \upsilon_\alpha^i \left(e_\alpha + \frac{p_\alpha}{\rho_\alpha} + \frac{\upsilon_\alpha^2}{2} \right)\right] = Q_\alpha^f + Q_\alpha^{nf} + Q_\alpha^{ir} \tag{3}$$

$$p_\alpha = p_\alpha(\rho_\alpha, T_\alpha) . \tag{4}$$

Here the summarizing is realized on the repeat indexes, $\delta^{i,j} = 0$ at $i \neq j$ and $\delta^{i,j} = 1$ at $i = j$, i =1,2,3. The terms $Q_\alpha^f, Q_\alpha^{nf}$ and Q_α^{ir} correspond to the energy exchange of α component per a unit of time in a unit of volume in consequence of elastic and non-elastic collisions and irradiation. For plasma as a whole one can write:

$$\sum_{\alpha=1}^{A} \zeta_\alpha = 0; \quad \sum_{\alpha=1}^{A} p_\alpha^i = 0; \quad \sum_{\alpha=1}^{A}\left(Q_\alpha^f + Q_\alpha^{nf} \right) = 0. \tag{5}$$

The equation of state of the thermally ideal gas is written in a form:

$$p_\alpha = n_\alpha k T_\alpha . \tag{6}$$

The three-componential plasma containing electrons, ions and atoms in the main state is considered in the present transaction. The applied model of such a mixture includes only the processes of ionization, recombination and is described by the simplest equation:

$$\frac{dn_e}{dt} = k_i n_A n_e - k_r n_e^2 n_i , \tag{7}$$

where k_i and k_r -coefficients of ionization and recombination.

At that the system of equations. (1) - (4) may be written in the form:

$$\frac{\partial \rho}{\partial t} + \sum_{i=1}^{3} \frac{\partial}{\partial x^i} \rho \upsilon^i = 0 , \tag{8}$$

$$\frac{\partial n_e}{\partial t} + \sum_{i=1}^{3} \frac{\partial}{\partial x^i} n_e \upsilon^i = k_i n_A n_e - k_r n_e^2 n_i , \tag{9}$$

$$\frac{\partial \rho u_i^i}{\partial t}+\sum_{j=1}^{3}\frac{\partial}{\partial x^j}\left(\rho u^i u^j + p\delta^{i,j}\right)=0\,, \tag{10}$$

$$\frac{dh}{dt}=\frac{1}{\rho}\frac{dp}{dt}-\frac{Q^{ir}}{\rho}\,, \tag{11}$$

$$\frac{5}{2}\frac{k\alpha\rho}{m_A}\frac{dT_e}{dt}=\frac{dp}{dt}+Q_e^f+Q_e^{nf}-Q_e^{ir}\,, \tag{12}$$

$$p=\rho R(T+\alpha T_e)\,;\quad p_e=\alpha\rho R T_e\,, \tag{13}$$

where

$$h=\frac{5}{2}R(T+\alpha T_e)+\frac{\alpha}{m_A}I\;; \tag{13a}$$

$$\alpha=n_e/(n_e+n_A)\approx m_A n_e/\rho\,;\quad R=k/m_A\,;\quad k_i=k_i(n_e,T_e)\,;\quad k_r=k_r(n_e,T_e)\,;$$

$$Q_e^f=Q_{eA}^f+Q_{ei}^f\,,\;\; Q_{eA}^f=(3/2)n_e n_A[8kT_e/(\pi m_e)]^{1/2}\times[(T-T_e)/T_e]kT_e(m_e/m_A)<\sigma_{eA}>;$$

$$Q_{ei}^f=n_e n_i(e^4/m_i)\left[8\pi m_e/(kT_e)\right]^{1/2}\left[(T-T_e)/T_e\right].$$

For the optically thick plasma the equations of Q_e^{nf} , Q^{ir} è Q_e^{ir} may be presented in the form [11]

$$Q_e^{nf}=-\left(I+\frac{5}{2}kT_e\right)\frac{dn_e}{dt}\,;\quad Q^{ir}=0\,;\quad Q_e^{ir}=0\,.$$

The equations of the state (8), motion (10) and energy (11) are written for plasma as a whole. In the energy equation for electrons (12) there is no kinetic energy of electrons as a small value comparatively to the internal energy magnitude. The equation (9) may be rewritten in the form

$$\frac{\partial\rho\alpha}{\partial t}+\sum_{i=1}^{3}\frac{\partial}{\partial x^i}\rho\alpha u^i=k_i\frac{\rho^2}{m_A}\alpha(1-\alpha)-k_r\frac{\rho^3\alpha^3}{m_A^2}\,.$$

As it was shown[11], the energy equation of electrons has the form of balance $T_e^3(T_e-T)=Cn_e$ in a rather wide range of parameters realizing in the supersonic source. At that

$$Q_e^f+Q_e^{nf}=0\,. \tag{14}$$

The system of equations (8) - (13) is solved by the numerical method of characteristics in the transaction[11].

Numerical methods of the calculation.

The method of establishment gained wide spread in gas dynamics[16]. To research the expending of the partly ionized gas the method of establishment was applied in the transaction [17] in the attachment to the calculation of the flow in the nozzle of the non-equilibrium plasma. The method is based on the use of non-stationary equation of plasma dynamics and obtaining the solution for the stationary flow as a limiting state at $t\to\infty$.

In the frames of the method of final volume [16] the differential equations describing the flow of the non-viscous non- heat-conductive non-equilibrium gas are written in the form of integral conservation laws. For the two-dimensional plasma flow in the Decart's coordinate system the equations may be presented in the form :

$$\frac{\partial}{\partial t}\int_{\Omega}F\,d\Omega+\int_{s}\overline{A}\,\overline{n}\,d\sigma=\Phi\,, \tag{15}$$

where

$$F=\begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{ra} \\ \boldsymbol{r}u \\ \boldsymbol{ru} \\ \boldsymbol{r}E \end{bmatrix},\ \vec{A}=\begin{bmatrix} \boldsymbol{r}\left(\overline{q}-\overline{\boldsymbol{l}}\right) \\ \boldsymbol{ra}\left(\overline{q}-\overline{\boldsymbol{l}}\right) \\ \boldsymbol{r}u\left(\overline{q}-\overline{\boldsymbol{l}}\right)+p\bar{\mathrm{i}}_x \\ \boldsymbol{ru}\left(\overline{q}-\overline{\boldsymbol{l}}\right)+p\bar{\mathrm{i}}_y \\ \boldsymbol{r}E\left(\overline{q}-\overline{\boldsymbol{l}}\right)+p\overline{q} \end{bmatrix},\ \Phi=\begin{bmatrix} 0 \\ \boldsymbol{f}_e \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{16}$$

Here $\bar{\mathrm{i}}_x$, $\bar{\mathrm{i}}_y$ - are the orts of the Decart's coordinate system, F - vector of conservative variables; $\overline{A}$ - vector of the conservative variables flow; s - limiting surface of the certain volumetric element, which has the external normal $\overline{n}$ and is moving with the velocity $\overline{\boldsymbol{l}}$; $\overline{q}=u\bar{\mathrm{i}}_x+\boldsymbol{u}\bar{\mathrm{i}}_y$ - vector of the gas flow velocity, u, $\boldsymbol{u}$ - components in the directions x and y of the Decart's coordinate system; $\tilde{n}$, p - density and pressure of the gas;

$E=\frac{3}{2}\frac{k}{m_A}(T+T_e)+\frac{\boldsymbol{aI}}{m_A}+\frac{q^2}{2}$ -specific total energy; f_e - mass velocity formed by a charged component as a result of elementary processes (ionization, recombination).

The difference of the present formulation from the regular one is that the cell velocity $\overline{\boldsymbol{l}}$ is included into the main equations and the volume of each element depends on time. For numerical calculations the equations have the advantages, which give the opportunity to operate with cells of unspecified form with mobile sides. It is convenient when calculating areas with free boundaries as far as correction of grid cells configuration is possible immediately during the calculation. The considered area of the flow is located between the surfaces of the body (including the edge of the nozzle), the surface of change, some surface, through which the plasma outflows the area and the symmetry surface. At the finite pressure in the environment the area of free expending beyond the edge of the nozzle is limited by shock waves. At the outflow into the vacuum extent of free expanding area becomes infinite. At the numerical simulation the calculation area is divided by two families of lines into a finite number of elementary volumes (cells). Plasma parameters of the fixed time t inside each cell are constant, average on the volume and changing only in going from one cell to another. One can define the position of any cell in the limits of the plotted differential grid with a number of indexes k, m (k=0, ..., K; m=0, ...,M).The equations (15) are realized for each elementary cell. The set of gas-dynamical parameters in all the cells at the time t is considered to be a well-known solution in the layer with the index n. The parameters in the layer n + 1 (t - time spacing) are calculated by means of application of explicit differential approximations of the equations (15) in the frames of the method of the finite volume

$$F^{n+1}_{k-1/2,m-1/2}=L(\Delta t)\prod_{b=1}^{e}L_a(\boldsymbol{t})L_c(\Delta t)F^n_{k-1/2,m-1/2}, \tag{17}$$

where the transition operator $L($ $t)$ has the form

$$\tilde{F}^{n+1}_{k-1/2,m-1/2}=F^n_{k-1/2,m-1/2}-\Delta t\left[\left(\overline{A}\,\overline{\boldsymbol{s}}\right)^n_{k-1/2,m}-\left(\overline{A}\,\overline{\boldsymbol{s}}\right)^n_{k-1/2,m-1}+\left(\overline{A}\,\overline{\boldsymbol{s}}\right)^n_{k,m-1/2}-\left(\overline{A}\,\overline{\boldsymbol{s}}\right)^n_{k-1,m-1/2}\right]/\,\Omega^n_{k-1/2,m-1/2} \tag{18}$$

Here the upper indexes indicate the numbers of time layers and the lower ones indicate the numbers of calculation grids. The values with integral lower indexes are defined on the side of the calculated cell. $\overline{\boldsymbol{s}}$ is the vector coinciding with the normal to the side by direction and equal to its surface by value. The method of calculation of the flow $\overline{A}$ is determined by the choice of a differential scheme. The modified Godunov's scheme is used in the present transaction. The operator (18) defines the values of parameters at the moment of time $t^n+\Delta t$, and according to their values defines them at the moment of time t^n under the condition that the grid is fixed and Φ = 0. As far as the solution of practical equations $(\Phi\neq 0)$ requires as usual smaller time spacing t, than the spacing Δt, the producing term is separated from the others and the operator $L_a(\boldsymbol{t})$ is applied

$$\approx{F}^{x+1/e}_{k-1/2,m-1/2}=\approx{F}^{x}_{k-1/2,m-1/2}+\boldsymbol{t}\Phi/\Omega^n_{k-1/2,m-1/2};\ \boldsymbol{e}=\Delta t/\boldsymbol{t} \tag{19}$$

repeated for each cell so many times till the sum of consecutive spacing $\sum\boldsymbol{t}$ becomes equal to the final time value t.

The effect of cells motion is taken into consideration due to the grid operator $L_c(\Delta t)$

$$F^{n+1}_{k-1/2,m-1/2} = \left[\tilde{\tilde{F}}^{n+1}_{k-1/2,m-1/2} \boldsymbol{s}^{n}_{k-1/2,m-1/2} + + \left(\tilde{\tilde{F}}\Delta \boldsymbol{s}\right)^{n+1}_{k-1/2,m} - \left(\tilde{\tilde{F}}\Delta \boldsymbol{s}\right)^{n+1}_{k-1/2,m-1} + + \left(\tilde{\tilde{F}}\Delta \boldsymbol{s}\right)^{n+1}_{k,m-1/2} - \left(\tilde{\tilde{F}}\Delta \boldsymbol{s}\right)^{n+1}_{k-1,m-1/2}\right] / \Omega^{n}_{k-1/2,m-1/2} \qquad (20)$$

Here $\Delta\Omega = f\left(\overline{s}, \overline{l}\right)$ - is the volume changing as a result of motion of grid sides moving with the velocity λ during the time interval Δt. At that the values $\tilde{\tilde{F}}$ on grid sides are not taken from the solution of the problem of break disintegration. They are defined proceeding from a new position of mobile sides of grid cells. Motion calculation of the external boundary of the area is realized analogous to that described in[14]. Motion of the external boundary of the area is discontinued when it reaches the conditional boundary of the area of the continuous flow. It is defined according to the methods[9]. After the definition of the new position of movable boundaries of the calculation area the grid generation is made in accord with a chosen law of the nodes distribution (for example, in the way as realized in [17,18]). According to this the calculation of one time spacing may be presented in such a consequence.

1) definition of the motion velocity of movable boundary sections in the calculation area [14];

2) calculation of intermediate values of parameters in the cells of the fixed grid (at the moment of time t^n);

3) definition of the new position of calculation grid nodes according to the prescribed law of distribution and their optimization;

4) calculation of unknown parameters distribution at the moment $t^{n+1} = t^n + \Delta t$.

Further one can consider the grid moving into one direction only. Normal to the side surface, which corresponds to the velocity, is only on those areas, which belong to the family of surfaces including disturbance front. The velocity of sides corresponding to another grid direction is equal to zero[11,16].

Simulation Results

One can consider a test problem about the characteristic of two-dimensional stationary expanding of non-equilibrium plasma by the example of the axially symmetric outflow from the conic nozzle with semi-opening angle $11{,}3^{\circ}$ and radius r_a = 1 cm (the analogous problem was considered in [13]). One can assume that the flow geometry on the edge of the nozzle corresponds to the flow in the source with the pole in the point of intersection of the generating line of the nozzle with the symmetry axis x (Fig.1). One can assume the parameters on the surface *àà* to be constant and corresponding to the experimental conditions M_c=*õ/a*=2.5; *õ*$_c$= 1.4 10^4 ì/c; T_c=2000 K; *ñ*$_c$=5 10^{-5} kg/m^3; p_c=830 Pa. The values $\boldsymbol{a}$ and T_e on the initial surface are determined from the equations (13) and (13à). Dimension of the calculation grid is changing during the calculation fulfillment from 10×80 to 100×80. Fig.1 and Fig.2 demonstrate the results of calculation of Mach number and pressure at the outflow of the ideal perfect uni-atomic gas (ã=1.67).

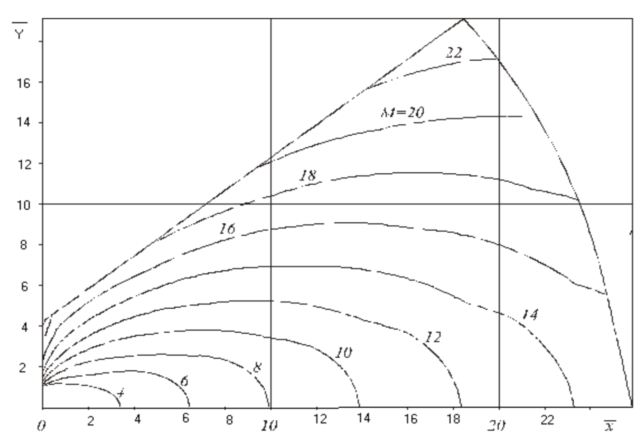

Fig.1 Equal level lines of Mach numbers in axially symmetric jet of the ideal perfect uni-atomic (ã=1.67) gas, which outflows from the round nozzle into the vacuum

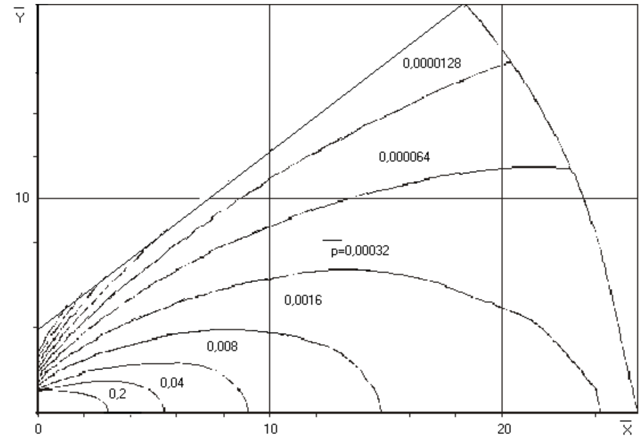

Fig.2 Equal level lines of pressure in axially symmetric jet of the ideal perfect uni-atomic (ã=1.67) gas, which outflow from a round nozzle into the vacuum.

The coordinates x and y relate to r_a: $\overline{x} = x / r_a$; $\overline{y} = y / r_a$. The pressure parameters relate to the pressure value on the surface *àà´*: $\overline{p} = p / p_c$.

The calculation values of Mach numbers on the axis of the hydrogen plasma jet are compared in Fig.3 with the Mach number on the axes of jets of ideal perfect uni-atomic (ã=1.67) and two-atomic (ã=1.4) gases.

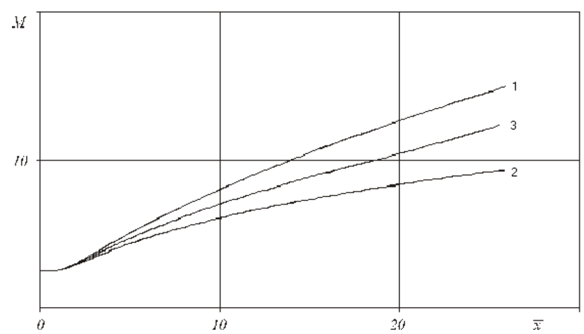

Fig.3 Comparison of the Mach numbers change in axes of hydrogen plasma jet, which outflows into the vacuum and the jets of the ideal perfect uni-atomic and two-atomic gases.1 . uni-atomic gas; 2 . two-atomic gas; 3 . plasma

Energy release in recombination expending plasma leads to the reduction of M in the flow area and more intensive turn from the symmetry axis comparatively to the entirely frizzed outflow corresponding to ã=1.67. In the present example the influence of relaxation processes on the flow geometry and the field of velocities and densities is comparatively not great that is explained by the moderating transition of ionization energy into translational degrees of freedom. The electron density variation along the axis X is presented in Fig.4

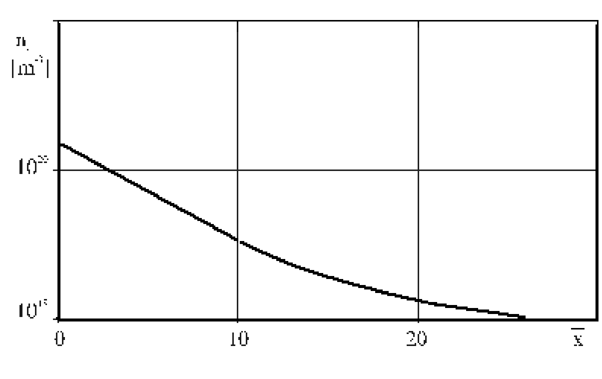

Fig.4 Variation of the electron density along the axis X.

For the assumed parameters the ionization energy on the edge of the nozzle constitutes nearly 20% of the total enthalpy. However, the release of a small portion of the accumulated energy only occurs as a result of a rapid freezing of ionization degree.(Fig.5).

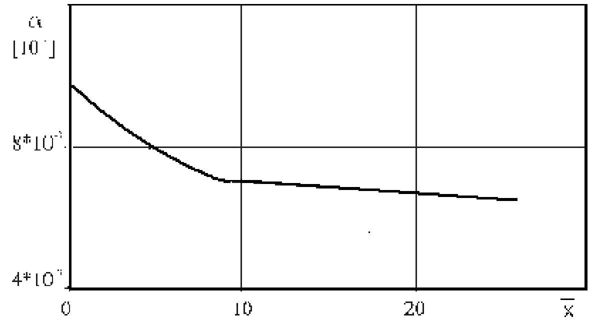

Fig.5 Variation of the ionization degree along the axis X.

Experiment

Experimental investigation of parameters of plasma jet from the round nozzle of RF-Thruster is executed on the vacuum chamber thrust stand of the National Aerospace University of Ukraine.
The experiments are conducted in both impulse and stationary regimes on the thruster. The working chamber of RF-Thruster model is presented as the coaxial line segment with the characteristic wave impedance $r = 75.Om$. One coaxial edge is opened and presents the shortened capacity in a form of the conic transition part connected with the coaxial of the smaller diameter. Another edge of the coaxial has the same conic transition part ending with the connector of the resistance 75 Om. Super high frequency energy from the power generator 1,5 kW is supplied through the connector. The coaxial section from current antinodes to voltage antinodes on the coaxial edge is presented as the quarter-wave resonator for the generator frequency 150 MHz.

Thus, in the described construction the automatically turning out of the coaxial into resonant regime occurs at the discharge initiating. At that it is necessary to choose the value of the shortened capacity so that the current antinodes always appear inside the construction. With the help of the conic transition part applied as the shortened capacity the needed value of the electrical field intensity of the order 140-170 V/cm is provided for the high-frequency break-down and the discharge initiating at the pressure in the coaxial 0,5-1 Òîrr. The plasma flow through the quarts nozzle with the diameter 10 mm outflows into the large vacuum tank with the volume 9,5 m^3 ñ and the working pressure 1,8 10^{-5} Òîrr. During the experiment the control of both incident and reflected waves in the coaxial is organized. The parameters of the plasma flow at the distance $\bar{x} = 25$ from the nozzle edge are measured by the electromagnetic probes and the floating-drift mass-spectrometer. The absorbed super-high-frequency power constitutes 47% of the supplied one at the thruster operation in the impulse regime with the pulse duration of RF-power $t = 4000 \ m\sec$ and the pulse frequency 2 Hz. In a case, the thruster operates in the continuous regime, this value constitutes 35%. The Mach number for the hydrogen at the distance $\bar{x} = 25$ is changing along the axis in the limits $M \approx 12-15$, the pressure is $\bar{p} = 24 \cdot 10^{-5}$ Torr, the electron density is $n_e \approx 1{,}8 \cdot 10^{18} m^{-3}$ and variation of ionization degree is $a \approx (5-7) \cdot 10^{-5}$. All that corresponds with the data of numerical calculations.(see Figures 1,2,4,5).

Conclusion

The serviceability of RF-thruster on the hydrogen is experimentally confirmed for both impulse and stationary regimes. The hydrogen plasma parameters of outflow from the nozzle of the coaxial RF-thruster into the vacuum correspond to the data of numerical calculations obtained with the use of the modified Godunov´s scheme. The calculations conducted on the base of the represented numerical methods showed strong correspondence with analogous data of other authors, obtained by the method of characteristics.

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