Probe Diagnostics of Rarefied Plasma Flows from Magnetoplasmodynamic Engines

V.A. Kotelnikov[1,]*, M.V. Kotelnikov[1,]*, S.S. Krylov[1,]**, Nguen Suan Thau[2,]***

[1] Moscow Aviation Institute, the National Research University (MAI), Moscow
[2] Le Quy Don Technical University, Hanoi, Vietnam

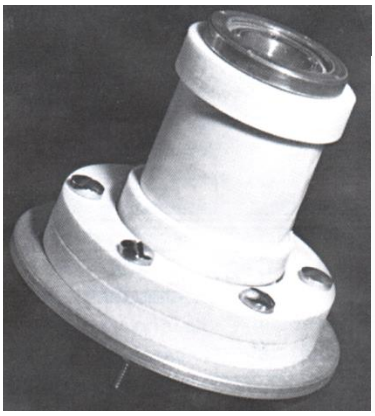
*mvk_home@mail.ru
**compgra@yandex.ru
***nguoikinhbac.rus@gmail.com

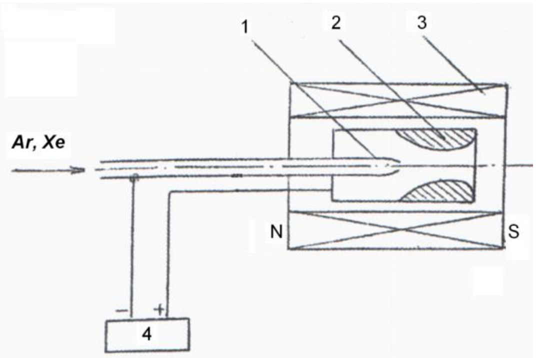
Abstract. Issues of probe diagnostics of rarefied plasma flows from magnetoplasmodynamic engines (MPDE) are considered, including the use of flat and cylindrical oriented probes as well as nonstationary probes. Results are given for probe measurements in jets coming from MPDE in test stand conditions and in the Earth ionosphere. The original methods of processing probe experiments are described and used. The distribution of the electron temperature, the concentration of charged particles, and the directed flow velocity along the jet radius is obtained under test stand conditions. In the conditions of the Earth's ionosphere, the temperature of electrons, the concentration of ions and electrons in an artificial plasma formation, as well as the potential difference between the rocket body and the environment, depending on the flight time and altitude above the Earth's surface, are studied. Probe diagnostics of plasma flows makes it possible to optimize the operating modes of this rarefied plasma source and expand the scope of its application. It can be used in semiconductor microelectronics and to solve a number of problems during space flights.
Keywords: rarefied plasma, magnetoplasmodynamic engine, probe diagnostics, flat and cylindrical oriented probes, nonstationary probe

1 Introduction

MPDE was tested in several organizations in particular, in the Moscow Aviation Institute, Energiya scientific development and production center, and in the Research Institute of Thermal Processes. It was first proposed, designed and tested in the Research Institute of Thermal Processes by Yuri Kubarev in 1957-1963.

The MPDE general view and its schematic diagram are given in Fig. 1. The engine has a power supply system including units for cathode electrical heating, lower pressure arc ignition between cathode and anode, solenoid winding power supply to create an axial magnetic field. Moreover, it has a working gas supply system, a cooling system (if necessary), a system of diagnostic equipment to study physical processes inside the propulsion unit and in the plasma jet flowing from it. Since the engine is intended for operation in ionosphere, it was placed in a special vacuum chamber with a respective system of vacuum equipment. For more details about design features of the engine, principles of plasma acceleration and the prospects of engine use, refer to [1].





a) b)

Fig. 1. MPD-engine; a) Engine general view; b) MPDE schematic diagram; 1 – hollow cathode with working medium supply; 2 – anode; 3 – magnetic system; 4 – power ource

From its invention to the present time, the MPDE has been improved in terms of its thrust characteristics, endurance capability, optimized weight, dimensional and power parameters. While discharge currents in the Kubarev engine were below several dozens of amperes, in other organizations, for example, in the Moscow Aviation Institute, discharge currents of plasma engines reached dozens of kiloamperes. This required detailed diagnostics of physical processes both inside the engine and in the rarefied plasma jet flowing from it.

V.A. Kotelnikov's research group carried out probe studies in jets flowing from low-current and high-current engines. The discharge voltage in both cases was below 50 V.

By the start of probe experiments on jets flowing from MPDE, the theory of probes was known from papers of Langmuir [2], Bohm [3], Laframboise [4] and a number of other American authors. The review of these papers is given in [5]. By that time, there were no reliable data on measurements in plasma flows. Such measurements were first performed in the Soviet Union at test stands of Yu.V. Kubarev in the Research Institute of Thermal Processes in 1966-1968 [6]. Due to the lack of a reliable theory, probes were calibrated before measurements in plasma flows by comparing the probe measurements with measurements by optical methods and methods of plasma UHF-radiography. The theoretical basis of probe diagnostics of plasma flows was developed much later. This theory is discussed to the fullest extent possible in [7,8,9]. It is convenient to diagnose plasma flows by flat geometry probes. In this case, the probe unit must include two independent probes the collecting surface of which must be located towards the flow and along the flow. One probe can also be used if its active surface is located towards the flow, but, this being the case, the processing method for the probe's volt-ampere characteristic (VAC) becomes more complicated. In both cases, the local values of the directional velocity of ions were measured in addition to the traditionally determined parameters of the plasma jet. Similar results can be achieved by using a probe unit consisting of two crossed cylindrical probes if the axis of one cylinder is directed perpendicular to the flow and the axis of the other one – parallel to the flow. If we move the probes along the jet radius and measure the distribution of ion concentration n_i and their directional velocity u_{d}, then we can calculate the flow rate of ions through the jet cross-section S

$$G_i = \int_S n_i u_d dS.$$

If the flow rate $G_{\mathrm{G}}$of gas supplied to MPDE is known, we can evaluate the degree of plasma ionization α

$$\alpha = \frac{G_i}{G_{\mathrm{G}}}.$$

The mathematical modelling of probe interaction with the surrounding plasma [7,8,9] and the mathematical modelling of the plasma flow from MPDE [10] provide additional information concerning the characteristic time of plasma relaxation τ and the characteristic thickness of the volumetric charge layer Δ near a body charged to a given potential φ and put into plasma.

If the probe is moved along the axis of the plasma jet from the nozzle exit and the potential distribution is measured along the axis, a positive potential jump can be found near the MPDE nozzle, which propagates to a distance of $(60 \div 80) r_D$ from the nozzle (r_D is the Debye-Huckel screening radius). The amplitude of the positive potential jump can reach several dozens of volts and depends on the directional flow velocity u_{d}, the ratio of ion and electron temperatures $\varepsilon = \frac{T_i}{T_e}$ and the nozzle radius R. The mathematical modelling of the jet [10] helped explaining the nature of this phenomenon. When the plasma from MPDE reaches the nozzle exit, the electrons as lighter and faster particles leave the nozzle faster than ions and form a negatively charged cloud to which a positively charged jet flows. The structure of the electronic cloud and positively charged jet is regulated by a self-consistent electrical field. The positive charge slows down ion movement from the nozzle, ion velocity falls down and this effect disappears at a distance of $(60 \div 80) r_D$ where the velocity returns to its initial value that was observed at the nozzle exit. If the engine thrust is measured with a balance, significantly differing results can be obtained depending on the balance position relative to the engine nozzle.

Let us note another interesting fact obtained using probes located in the plasma flow from MPDE. From the probe located under the "floating" potential, a signal was supplied to oscilloscope plates where chaotic potential oscillations were found. Within the considered pressure range of $(5 \cdot 10^{-2} \div 1)$ Pa and magnetic fields

($\mathrm{H} = 0 \div 8 \cdot 10^4 \frac{\mathrm{A}}{\mathrm{m}}$), the oscillation frequency varied within $(5 \div 150)$ kHz at the maximum amplitude ~ 1 B [11]. It was not possible to explain the reason for these oscillations within the framework of classical local physics. Their nature was explained only after non-local physics developed by professor B.V. Alexeyev [12] appeared. In non-local physics, two neighboring physically infinitesimal volumes in plasma exchange charged particles in a chaotic manner, so that an addend changing under the chaotic law is added to the Poisson equation defining the self-consistent electrical field in the right part. The solution of the Poisson equation can be found in the potential component that fluctuates and manifests itself in the probe experiment. The theory states that oscillating processes substantially depend on the Knudsen number that equals the ratio between the mean free path of particles and the characteristic size of the problem.

To conclude the review of probe method capabilities in MPDE diagnostics, let us note a principal ability to measure the ion temperature T_i in addition to the electron temperature. To find T_i, the plasma relaxation time τ_{exp} must be measured near the probe after a pulse change in its potential. The theoretical values τ_{theor} can be found in [7,8,9] depending on the characteristic parameters of the problem $r_0 = \frac{r_p}{r_D}$ and $\varepsilon = \frac{T_i}{T_e}$ (r_p is the geometric probe size). If τ is measured in the probe experiment by supplying a potential pulse to the probe and it is compared with τ_{theor}, then T_i can be obtained from such comparison. The physical explanation of this result lies in the fact that the plasma relaxation time is defined by heavy particles – ions, and τ_{theor} is included in T_i.

Further, in section 2, three original author's methods for processing probe characteristics obtained in a rarefied plasma stream flowing from the MPDD will be proposed. Method No. 1 is based on the ion branch of the VAC and the initial section of the transition branch for plane geometry probes. Method No. 2 corresponds to a flat probe oriented towards the plasma flow flowing out of the SDA. Method No. 3 involves probes of cylindrical geometry in a rarefied plasma flow. Section 3 presents some results of probe measurements in the plasma flow flowing from the SDA. Here are probe measurements in bench conditions and probe measurements in ionospheric conditions. The conclusion is presented in section 4.

2 Processing methods for probe characteristics obtained in rarefied plasma flows from MPDE

Currently, when conducting probe experiments, a different, more modern probe scheme is used. Let's give a brief description of it.

A block diagram of the electronic device is given in Fig. 2.

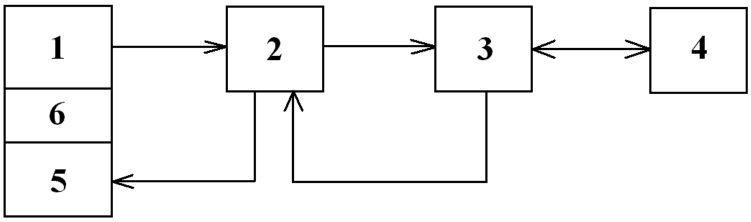


Fig. 2. Probe device block diagram; 1 - probes; 2 - probe current meter; 3 - input/output device; 4 - computer; 5 - anti-probe; 6 - plasma formation

Plasma formation (6) flows around probes (1) and anti-probe (5) and is a conductor closing the electrical circuit of probes. An anti-probe can be a cathode, anode, chamber's conductive wall, or any other large body (as compared to the probe size) put into plasma. A potential difference is created between the probe and anti-probe. Probe current occurring during this process is supplied to the current meter (2). Output signals of this device are voltages directly proportional to probe currents. These voltages are supplied to special input-output devices (3) (IOD) IUSDAQ-U 120816 that convert them into a digital form as voltage codes. Device (2) also makes it possible to measure the "floating" potential. After conversion into the digital form, potential values are stored in the memory of computer (4) for processing information and setting the next potential values for the probes. The operating mode of device (2) is defined by a computer program. Control signals are supplied via IOD and switch device (2) to the status of executing the preset algorithm. The potentials supplied to the anti-probe are formed in (2) using the PWM (pulse width modulation) signals coming from IOD. This way of potential supply (to the anti-probe rather than the probe) makes it possible to avoid couplings and create an improved layout diagram. Since IOD forms PWM of positive polarity only, this device forms a special control signal that allows changing the potential polarity when it is required to supply a negative potential to the probe.

2.1 Method No. 1 based on VAC ion branch and initial section of the transition branch for probes of flat geometry

Let us consider the case of using two flat oriented probes one of which is located perpendicular to the approach flow and the other – parallel to that flow [7,8,9]. The labor intensity of processing is substantially reduced if the flat probe radius r_p is great as compared with the Debye-Huckel screening radius r_D:

$$r_p \geq 500 r_D \tag{1}$$

As calculation experiments showed [8], in this case for the flat probe oriented along the flow, the end and marginal effects can be neglected since they take place only in the boundary areas of the probe surface near edges, and they can be neglected if condition (1) is fulfilled. The rest part of the probe surface does not experience the effects of edges (marginal effect) and directional velocity (end effect). Therefore, it is possible to use the Bohm formula obtained for resting plasma. This conclusion was obtained theoretically [7,8,9] and experimentally confirmed. We find ion concentration n_i from the Bohm formula:

$$n_i = \frac{I_{\text{exp}}}{C \cdot S_{\text{probe}} \cdot e \cdot \sqrt{\frac{2kT_e}{m_i}}}\,, \tag{2}$$

where $\mathrm{C} = 0{,}8$; $S_{\text{probe}} = \pi r_p^2$; $e = 1{,}6 \cdot 10^{-19}$ Coulomb; $k = 1{,}38 \cdot 10^{-23}\ \frac{\mathrm{J}}{\mathrm{K}}$; m_i is the ion mass of plasma forming gas; I_{exp} is the experimentally measured current at sufficiently high negative potential of the probe; T_e is the electronic temperature determined using the classical method in the initial section of the VAC transition branch.

If condition (1) can not be fulfilled, two approaches are possible [8]:

Using the method of guard electrodes to remove marginal and end effects with their help;

Using a smaller probe. In this case, the processing requires the use of a cyclic process with a set of VACs at various directional velocities and different $r_0 = \frac{r_p}{r_D}$.

To find the directional velocity of flow u_{d}, we use the Langmuir formula [4] for current $I_{\perp\text{probe}}$ to the probe directed perpendicular to the flow in case of negative potential φ_p:

$$u_{\text{d}} = \left[\left(\frac{I_{\perp\text{probe}}}{en_i S_{\text{probe}}}\right)^2 - \frac{2e|\varphi_p|}{m_i}\right]^{\frac{1}{2}} \tag{3}$$

Apart from the found values T_e, n_i, u_{d}, the following values are found:

"Floating body" potential φ_{float}. This is a point on the VAC diagram where the total current equals zero;

Space potentialφ_{appr} – under the approximated formula [8]

$$\varphi_{\text{appr}} \cong \varphi_{\text{float}} + \frac{kT_e}{e} \ln\left[\frac{1}{3{,}2}\left(\frac{4}{\pi}\frac{m_i}{m_e}\right)^{\frac{1}{2}}\right]; \tag{4}$$

Relaxation time in plasma under diagrams resulting from calculational experiments and given in [8];

Volumetric charge layer thickness Δ – according to the results of calculational experiments from [8];

Ion temperature T_i. For this, additional experiments with a pulse change in the probe potential are required to obtain the experimental value τ_{exp}.

2.2 Method No. 2 for processing the VAC of the flat probe oriented towards plasma flow from MPDE

If only a flat probe located perpendicular to the plasma flow was used in the experiment, then both VAC branches are used in processing: ion and electron.

The following is assumed to be known: probe area S_{probe} provided condition (1) is fulfilled; mass of plasma-forming gas ions m_i; ion component temperature T_i (T_i is evaluated as one of additional considerations or is found experimentally using the nonstationary probe); experimental VAC of a flat probe including ion and electron branches.

The following option of VAC processing is proposed:

The “floating” potential φ_{fl} is found as the potential of the point where the total current to the probe equals zero;

The space potential φ_{space} is found using the point of transition of the VAC rising section to electron saturation current. To find φ_{space} more accurately, the dependence between the derivative $\frac{dI_{\text{electr}}}{d\varphi}$ and the potential φ is used. The maximum of this dependence is found as φ_{space};

The electron temperature T_e is calculated using formula (4)

$$T_e = \left(\varphi_{\text{appr}} - \varphi_{\text{float}}\right)\frac{e}{k}\left\{\ln\left[\frac{1}{3{,}2}\left(\frac{4}{\pi}\frac{m_i}{m_e}\right)^{\frac{1}{2}}\right]\right\}^{-1};$$

The function of electron distribution is found using Dryuvesteyn energies $f(W)$

$$f(W) = \frac{4}{e^3 S}\left(\frac{m_e W}{2}\right)^{\frac{1}{2}}\frac{d^2 I}{d\varphi^2},$$

where the second derivative $\frac{d^2 I}{d\varphi^2}$ is found from the VAC rising section;

Function $f(W)$ is normalized

$$f_{\text{norm}}(W) = f(W)\left[\int_0^\infty f(W)dW\right]^{-1};$$

The normalized function $f_{\text{norm}}(W)$ is used to find the average energy of electrons and their average temperature

$$\langle W\rangle = \int_0^\infty W f_{\text{norm}}(W)\,dW, \qquad \langle T_e\rangle = \frac{2}{3}\frac{\langle W\rangle}{k}.$$

The last formula for T_e is more accurate than the formula given in Item 3 of the algorithm;

Electron concentration is found

$$n_e = n_i = \frac{1}{\langle W \rangle} \int_0^{\infty} W f(W) dW;$$

Directional ion velocity is calculated under formula (3);

Parameters τ, Δ, T_i are found similar to method No. 1.

The following remarks can be made using method No. 2:

Since the chaotic velocity of electrons is much higher than their directional velocity, it is assumed that the directional velocity has a low effect on the VAC electron branch;

MPDE has an outer axis-symmetric magnetic field that partially gets into the plasma flow from the nozzle. Electrons in the field can be magnetized, which may distort the VAC electron branch;

To find some plasma parameters using the VAC electron branch, statistical approaches are employed. Since electron distribution functions near the probe are not Maxwell functions [8], this must be taken into account in building VAC processing methods.

Taking into account these remarks, we can expect that the error in finding parameters using method No. 2 will be higher than in method No. 1.

2.3 Method No. 3 for processing VAC of the probes of cylindrical geometry in the rarefied plasma flow from MPDE

Let us consider an assembly of two cylindrical probes crossed at right angle. The symmetry axis of one of them must be directed towards the flow, the axis of the other – perpendicular to it. Let us assume that the cylindrical probe length l_p is much longer than its radius r_p. This assumption allowed reducing the dimensionality of the problem’s mathematical model in phase space. Moreover, in this case, the current to the cylinder end can be neglected as compared with current to its side surface. If the cylindrical probe is directed along the flow, its current will be defined by charged particles only going to the side surface by means of chaotic movement in plasma and it does not depend on directional movement. Therefore, the VAC processing of such probe can be done using the method for resting plasma. The elementary theory of such probe was developed by Langmuir during 1924-1932 [2], improved by Bohm in 1949 and finally developed to the current level by Laframboise in 1966 [3]. He obtained the set of VACs necessary for practical probe measurements. While Laframboise solved a stationary probe problem that was called the Vlasov-Poisson problem in the modern language, the research group of V.A. Kotelnikov obtained the same set of VACs in 1979-1980 by solving the Vlasov-Poisson nonstationary problem [13-14]. The nonstationary approach appeared to be so productive that it allowed solving a whole number of other probe problems, in particular, taking into account the directional velocity [7,8,9], magnetic field, etc.

Let us give a VAC processing sequence in this case. Radius r_p and probe length l_p, mass of plasma-forming gas ions m_i, ion temperature T_i (this temperature can be measured by a nonstationary probe or assessed in any manner), probe potential φ_p and its respective probe current I_p are deemed to be known. Since the probe problem is solved after bringing equations to a dimensionless form, we will need some scales:

$$M_r = r_D = \left(\frac{\varepsilon_0 k T_i}{n_i e^2}\right)^{\frac{1}{2}}; \quad M_\varphi = \frac{kT_i}{e}; \quad M_j = \frac{M_I}{M_r^2} = en_i\left(\frac{2kT_i}{m_i}\right)^{\frac{1}{2}}$$

To calculate n_i, the following iterative process is built:

Ion concentration n_{i1} is designated. For example, it can be taken using the Bohm formula. Scales $M_{r1} = \left(\frac{\varepsilon_0 kT_i}{n_{i1}e^2}\right)^{\frac{1}{2}}, M_\varphi = \frac{kT_i}{e}$ and dimensionless parameters of the problem $r_{01} = \frac{r_p}{M_{r1}}, \varphi_0 = \frac{\varphi_p}{M_\varphi}, \varepsilon = \frac{T_i}{T_e}$ are calculated. The electron temperature is found using the rising part of the VAC electron branch

$$T_e = \frac{e}{k}\left[\frac{d \ln j_e}{d\varphi_p}\right]^{-1},$$

where $j_e = \frac{I_e}{2\pi r_p l_p}$;

VAC set [7] $j_i = j_i(r_0, \varphi_0, \varepsilon)$ is used to find the dimensionless current density j_{i1} corresponding to the parameters $(r_{01}, \varphi_0, \varepsilon)$;

Using the formula for current density scale

$$M_j = \frac{M_i}{M_r^2} = en_{i2}\left(\frac{2kT_i}{m_i}\right)^{\frac{1}{2}} = \frac{I_p/(2\pi r_p l_p)}{j_{i1}}$$

we find $n_{i2} = \frac{I_p/(2\pi r_p l_p)}{e j_{i1}\left(\frac{2kT_i}{m_i}\right)^{\frac{1}{2}}}$;

If $|n_{i2} - n_{i1}| < \delta$ where δ is low value set in advance, the calculation stops and $n_i = n_{i2}$ is assumed. Otherwise, we go to Item 1 and repeat the calculation cyclically until results converge.

To find the directional flow velocity, we use the characteristic of a probe oriented perpendicular to the flow. A set of VACs of such probes was first obtained by the research group of V.A. Kotelnikov [7] and given in Fig. 2. Curves in the figure are given in non-dimensional form $M_{u_i} = \left(\frac{2kT_i}{m_i}\right)^{\frac{1}{2}}$.

The mathematical model of the cylindrical probe located across the flow shows that current density (j_i) depends on four dimensionless parameters: $r_0 = \frac{r_p}{M_r}, \varphi_0 = \frac{\varphi_p}{M_\varphi}, u_0 = \frac{u_\mathrm{d}}{M_{u_i}}, \varepsilon = \frac{T_i}{T_e}$. Fig. 3 shows that as the dimensionless velocity u_0 rises, VACs with various r_0 approach each other and gradually converge into a single line (in case of $u_0 > 7$). Physically, this means that for $u_0 > 7$, the effect of directional velocity prevails over the electrical field effect and current to the probe is defined by directional movement only

$$j_i = en_i u_\mathrm{d} \tag{5}$$

In case of lower velocities $3 < u_0 < 7$, high results are demonstrated by the Langmuir formula [2]

$$j_i = en_i u_\mathrm{d} \left(1 - \frac{e\varphi_p}{\frac{m_i u_\mathrm{d}^2}{2}} \right)^{\frac{1}{2}} \tag{6}$$

In case of $u_0 < 3$, the formula (6) gives the overestimated value j_i, since it was obtained in the limit case of orbital movement and gives the upper limit value of current to the probe in rarefied plasma [5]. In this case, a cyclic algorithm must be built similar to the cylindrical probe located along the flow but using VAC in Fig. 2.

In this case, apart from values T_e, n_i, u_d, all other parameters can be obtained: φ_float, φ_appr, τ, Δ, T_i.

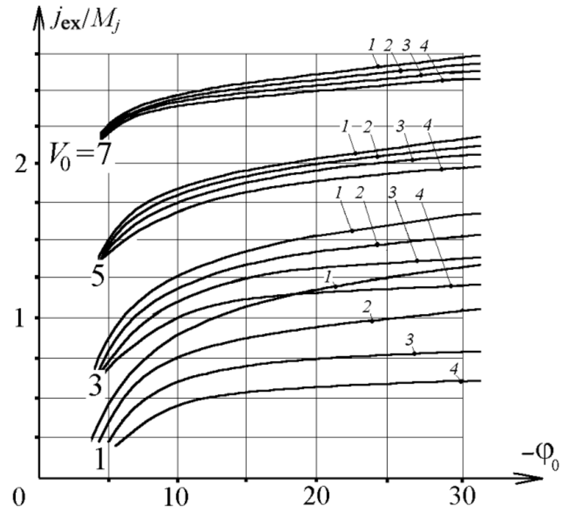


Fig. 3. Cylindrical probe VAC in transverse flow of rarefied plasma ($\varepsilon = 1$); 1 – $r_0 = 3$; 2 – 10; 3 – 30; 4 – 100

3 Some results of probe measurements in the plasma flow from MPDE

3.1 Probe measurements in test stand conditions

A flat disc-shaped probe of stainless steel was installed on the jet axis 6 cm from the nozzle exit. Evaluations showed that the dimensionless probe radius is $r_0 \cong 250$, which is close to criterion (1). This means that the edge effects can be neglected so the dependence on the probe geometry disappears. The discharge conditions of the experiment are as follows:

Discharge current in plasma source $I_{\text{disch}} = 1{,}5$ A (low-current discharge);
Discharge voltage $U_{\text{disch}} = 48$ V;
Working chamber pressure $P = 8 \cdot 10^{-4}$ torr;
Plasma-forming gas: air.

VACs obtained in the experiment were processed using method No. 2. Processing results:

Electron temperature $T_e = 13{,}1$ eV;
Concentration of charged particles $n_{i,e} = 3{,}2 \cdot 10^{16}$ m^{-3};
Directional movement velocity along jet axis $u_{\text{d}} = 16$ km/s;
Space potential $\varphi_{\text{appr}} \cong 50$ B;
Volumetric charge layer thickness near probe $\Delta \cong 0{,}5 \cdot 10^{-3}$ m;
Characteristic time of relaxation in plasma $\tau \cong 0{,}2 \cdot 10^{-6}$ s.

Let us note that the measurement time using the automated experiment system was several minutes. Thermal flows to the probe over this time did not result in its overheating so no forced cooling was required.

Let us give the characteristic results of the experiment in a high-current discharge. The experiment was carried out at the test stand of the MAI department of physics.

In case of high discharge currents, the probes were exposed to high thermal flows. As a result, probes were covered with a conductive film due to cathode and anode material erosion, which changed their active surface. Therefore, the time of probe presence in the plasma flow was minimized and it was also cooled down in a forced manner.

The experiment employed two flat probes with parallel and perpendicular orientation of their surface relative to the flow velocity vector. The discharge conditions of the experiment are as follows:

discharge current in plasma source $I_{\text{disch}} = 1400$ A;
discharge voltage $U_{\text{disch}} = 50$ V;
working chamber pressure $P \approx 10^{-3}$mm Hg.;
plasma-forming gas: argon, flow rate $10^{-3}\,\frac{\text{g}}{\text{s}}$;
the experiment was done at several points along the jet radius 20 cm from the nozzle exit.

VACs obtained in the experiment were processed using method No. 1. The processing results are given in Fig. 4.

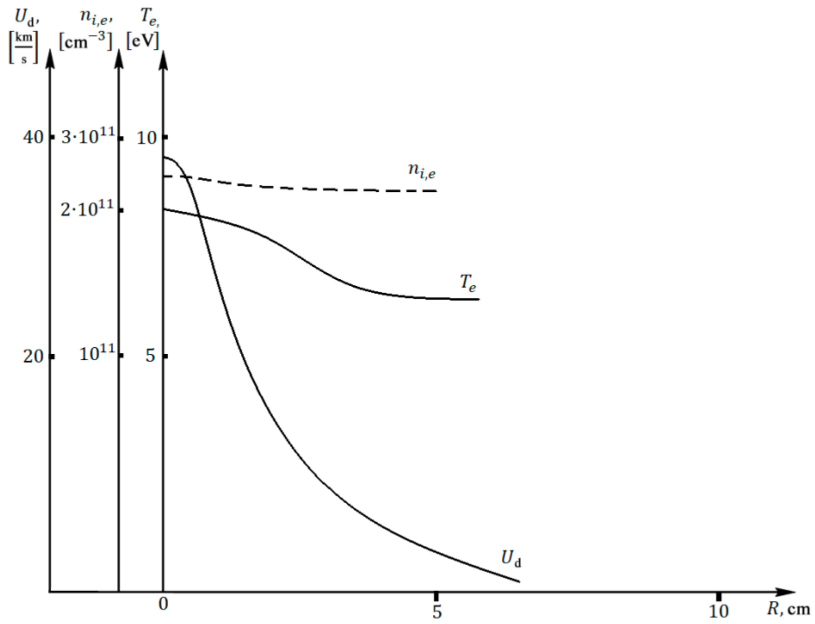


Fig. 4. 4. Distribution of electron temperature T_e, concentration of charged particles $n_{i,e}$ and directional flow velocity U_d along the jet radius

3.2 Probe measurements in ionosphere conditions

After the test stand study, a low-current MPDE was tested in ionosphere conditions [7,8,9]. Its weight, dimensions and energy consumption were minimized. As a result, the electrical power of the source was 3 kW, the weight (without power source) was 3.5 kg, the time of active operation was 300 s, the working gas (air) flow rate was 1 ÷ 3 mg/s. The electrical probes were placed 10, 50 and 550 mm from the nozzle exit. The probe closest to the nozzle was flat and had an active surface of 1.5 mm2, other two probes were cylindrical. The distant probe was installed on a rod that was turned when rocket flaps opened. The probe measurement layout differed in a wide range of measured probe currents, had a coupling with the onboard power source and was coordinated with telemetry. The MPDE was installed on the meteorological rocket brought to an altitude of ~160 km above the Earth surface where the propulsion unit and the probe measurement system were turned on. Then the rocket moved inertially gradually losing altitude and engine power was turned off at ~50 km.

Fig. 5 gives measurement results for the parameters of the plasma flowing from MPDE into the ionospheric space at launch No. 1, and Fig. 6 gives the same for launch No. 2.

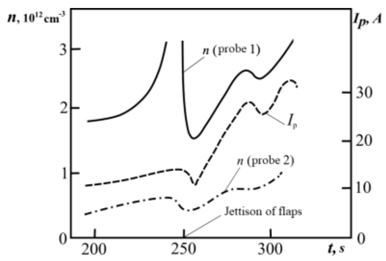


Fig. 5. 5. Dependence of ion concentration in artificial plasma formation on time (launch No. 1)

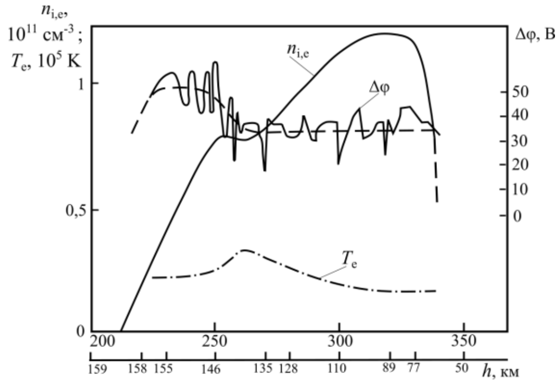


Fig. 6. 6. Dependence of artificial plasma formation parameters on time (altitude) (launch No. 2), $\Delta\varphi$ is the potential difference between the rocket body and the environment

During the first launch, the flaps covering the MPDE container were released only after a repeated command from the Earth in 249 seconds, while the engine was turned on in 184 seconds and operated inside the enclosed volume. This was reflected on the distribution curves of plasma jet parameters.

Based on the curves given in Figures 5 and 6 and other available data (except for MPDE and probes, the bearing platform also accommodated a magnetometer, an impedance probe, two mass spectrometers, a Geiger counter tube), the following conclusions can be made:

The engine operation mode (in particular, voltage and discharge current) greatly depends on pressure on the nozzle exit. As pressure rises, the discharge current increases and the concentration of charged particles synchronously follows the change in the discharge current. Several typical engine operation modes were found.

The potential of the rocket related with the engine body greatly changes during the flight. Potential change scale is ~20 V.

During engine operation, the body potential made oscillations relative to the space potential with a frequency of several Hertz and an amplitude of about 10 V.

The plasma flowing from the engine nozzle had a substantial effect on other instruments installed on the bearing platform.

Engine operation modes were found when the plasma jet is distanced from the rocket body and occupies significant volumes. This does not occur in other modes.

More detailed data on MDPE operation modes and plasma jet flowing from its nozzle can be found in [7,8,9].

4 Conclusion

The magnetoplasmodynamic engine discussed in this article has undertaken multiple tests in test stand conditions and ionosphere plasma and, if slightly modified, can be used to solve various tasks in space exploration. The detailed consideration of possible MPDE applications can be found in [1]. Apart from the aviation and space field, the MPDE is already used in high technologies (plasma chemistry, plasma coating, neutralization of induced charges in communication satellites, etc.).

References

1. Kubarev Yu.V. Flight to Mars, electric propulsion engines of today and tomorrow // Science and technology in industry, 2006, No. 2, pp. 19-35;
2. Langmuir I., Mott – Smith H.M. Phys. Rev. 26, 727, 1926;
3. Bohm D. Birhop E.H.S. The characteristics of electrical discharges in magnetic fields (A. Guthrie eds.) Ch. 2 Mc Grew-Hill, New York, 1949;
4. Laframboise J. Theory of spherical and cylindrical Langmuir probes in a collisionless plasma at rest (rarefied gas dynamics) ed. J. H. Lanw – Academic press, 1966, v. 11, N4, pp. 22-42;
5. Chan P., Telbot L., Turyan K.I. Electrical probe in stationary and moving plasma.: Theory and application. Moscow: WORLD, 1972, 202 p.;
6. Kotelnikov V.A., Shirokov M.F., Kubarev J.V. // 7th Intern. Conf. Phenomena Ionized Gases, Vienna, 1667, pp. 477-479;
7. Kotelnikov V.A., Kotelnikov M.V. Probe diagnostics of plasma flows. Moscow. Izhevsk Research Center Regular and Chaotic Dynamics, 2016, 440 p.;
8. Kotelnikov V.A., Filippov G.S., Kotelnikov M.V. Diagnostics of plasma flows using oriented probes. Published by Lambert Academic Publishing, Deutschland, 2016, 332 p.;
9. Ignakhin V. S., Sysun V. I. Modeling of the ion current on a probe in plasma taking into account ionization and collisions with atoms. Part 2: Cylindrical probe / / Plasma Physics, 2018, Vol. 44, No. 10, pp. 812-819;
10. Kotelnikov V.A., Morozov A.V., Kotelnikov M.V. Mathematical modelling of rarefied plasma flow interaction with magnetic field, Moscow: Published by MAI, 2015, 167 p.;
11. Kubarev Yu.V., Kotelnikov V.A. Low-frequency resonance electrical oscillations in non-isothermal plasma flow // Technical Physics Journal, Vol. XXXVIII, Issue 11, 1968, pp. 1869-1871;
12. Alexeev B.V. Non-local physics. Non-relativistic theory. Published by Lambert Academic Publishing, Deutschland, 2011, 500 p.;

13. Alexeev B.V., Kotelnikov V.A., Novikov V.N. Calculation of a disturbed zone near probe by numerical method // Plasma physics, 1979, Vol. 5, No. 4, pp. 920-922;
14. AlexeevB.V., Kotelnikov V.A., Novikov V.N. Nonstationary Langmuir probe // Thermophysics of high temperatures, 1980, Vol. 18, No. 5, pp. 1062-1065.