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DETERMINATION OF KINETIC PARAMETERS OF SUPERSONIC PLASMA FLOW OF a GAS-DISCHARGE SOURCE FROM CURRENT MEASUREMENT by AN INSULATED PROBE SYSTEM

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Метою роботи є розробка процедури відновлення кінетичних параметрів заряджених частинок у надзвуковому струмені газорозрядного джерела беззіштовхувальної плазми за результатами вимірювань струму, що збирається ізольованою зондовою системою з поперечно обтічними циліндричними електродами. На основі отриманих раніше математичної моделі збирання струму ізольованою зондовою системою та асимптотичного рішення для зондового струму в області насичення електронів отримано співвідношення, що зв'язують температуру, спрямовану швидкість іонів і температуру електронів надзвукового струменя плазми з результатами вимірювань зондових струмів.

Досліджено вплив параметрів зондової системи та похибки вимірювання струмів та напруги на достовірність діагностики газорозрядної плазми двоатомного робочого газу. В рамках моделі збирання зондового струму для області насичення електронів отримано числові та аналітичні оцінки похибок відновлення кінетичних параметрів плазми залежно від геометричних параметрів зондової системи, точності вимірювання зондових струмів та потенціалів зміщення зонда щодо потенціалу опорного електрода. Визначено оптимальні відношення площин вимірювального та опорного електрода ізольованої зондової системи та умови вимірювань зондових струмів для адекватного оцінювання середньої кінетичної енергії та швидкості спрямованого руху іонів у надзвуковому струмені газорозрядної плазми. Наведено апріорні кількісні характеристики впливу похибок зондових вимірювань на достовірність відновлення кінетичних параметрів заряджених частинок.

Розроблена процедура та отримані оцінки похибки відновлення кінетичних параметрів плазми дозволяють вибрати параметри зондової системи та оцінити необхідну точність вимірювань під час планування та проведення експериментів з діагностики лабораторної плазми.

Ключові слова: *струмінь беззіштовхувальної плазми, кінетична енергія заряджених частинок, швидкість спрямованого руху іонів, математична модель збирання струму, область насичення електронів, оцінки похибки відновлення параметрів.*

The aim of this work is to develop a procedure for determining the kinetic parameters of charged particles in a supersonic jet of a gas-discharge source of collisionless plasma by measuring the current collected by an insulated probe system of cylindrical electrodes placed transversely to the jet. Based on the authors' mathematical model of current collection by the above-mentioned probe system and asymptotic solution for the probe current in the electron saturation region, the ion temperature and directed velocity and the electron temperature are related to the measured probe current.

The effect of the probe system parameters and the current and voltage measurment error on the reliability of diagnostics of a diatomic gas-discharge plasma is studied. Within the framework of the probe current collection model for the electron saturation region, numerical and analytical estimates of the errors in determining the kinetic plasma parameters are obtained as a function of the geometric parameters of the probe system, the accuracy of probe current measurement, and the bias potential of the probe relative to the potential of the reference electrode. The measuring-to-reference electrode area ratio and the probe current measurement conditions optimal for adequate estimation of the average kinetic energy and the directed velocity of ions in a supersonic gas-discharge plasma jet are determined. A priori quantitative characteristics of the effect of the probe measurement errors on the reliability of the determination of the charged particle kinetic parameters are given.

The reported procedure and estimates of the error in kinetic plasma parameter determination allow one to choose the probe system parameters and estimate the required measurement accuracy when planning and conducting experiments on laboratory plasma diagnostics.

Keywords: *collisionless plasma jet, kinetic energy of charged particles, ion directed velocity, mathematical model of current collection, electron saturation region, parameter determination error estimate.*

Introduction. Physical modeling of the interaction of structural elements and on-board equipment of spacecraft with ionospheric plasma is an important stage in the development of space technology. The most adequate comprehensive modeling of ionospheric conditions in orbit can be implemented using a gas-discharge plasma source with ion acceleration in the electric field of the jet [1, 2].

Diagnostics of a supersonic flow of laboratory low-temperature plasma is usu-

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ally carried out using single stationary cylindrical Langmuir probes using the wall of a vacuum chamber as a reference electrode [3]. In our previous works [4 – 6], it is theoretically shown that the insulated probe system (IPS) of cylindrical electrodes significantly increases the information content of probe measurements in the jet of a gas-discharge plasma. Provided that the acceleration of ions occurs in the electric field of the source jet, an asymptotic solution for the probe current in the electron saturation region is obtained for the diatomic plasma. Procedures for carrying out probe measurements in the core region of the jet are proposed to determine the degree of ion dissociation, electron density and temperature.

In this article, under the assumptions made, relationships are obtained between the kinetic parameters of charged particles (such as temperature and bulk velocity of ions, electron temperature) in the plasma jet and the probe currents measured by the IPS. The influence of the geometric parameters of the probe system, the current and voltage measurement error on the reliability of the determination of the plasma kinetic parameters is studied. The optimal for practical use IPS's electrodes areas ratio and the range of the bias potential are determined.

Problem formulation. The problem of electric current collection by an IPS, cylindrical electrodes of which are oriented transversely to the bulk velocity in the supersonic flow of gas-discharge plasma of a diatomic gas is considered [4 – 6]. The acceleration of molecular ions of mass m_i and atomic ions of mass $m_i/2$ occurs in the electric field of a jet flowing into a vacuum chamber [1].

We assume that the plasma is Maxwellian, collisionless, quasineutral, there is no magnetic field, the temperatures of atomic and molecular ions are equal ($T_{i,1} = T_{i,2} = T_i$), the mass velocities of atomic $V_{i,1}$ and molecular V_i ions satisfy the relation $V_{i,1}/V_i = \sqrt{2}$. The degree of ion dissociation in the plasma jet is characterized by the parameter $\eta = n_{i,1}/n_e$, where $n_{i,1}$ is the density of atomic ions, n_e is the electron density.

The IPS is located in the core area of the jet (where plasma parameters don't change in any direction perpendicular to the jet center line). It consists of a measuring electrode (probe) with current-collecting surface area of S_p, a reference electrode with the area of S_{cp}. Electrodes have electrical contact with the plasma, and they are electrically insulated from the body of the vacuum chamber. The base radius of the probe r_p and the reference electrode r_{cp} are significantly smaller than their lengths, and the end surfaces of the electrodes are insulated from the plasma. The base radii of the electrodes satisfy:

$$r_p/\lambda_d \leq 1 \,, \quad r_{cp}/\lambda_d < \xi^* = 3 - 10,$$

where λ_d is the Debye length in an unperturbed plasma, ξ^* is such value of r_{cp}/λ_d, which restricts the applicability of the Langmuir formula for ion current to a transversely oriented cylinder [7].

Let's also assume very little electrostatic and gas-dynamic influence of electrodes on each other and on the surrounding plasma flow, the absence of the emission current from the electrodes, free-molecular regime of plasma flow around the electrodes.

The purpose of this work is to develop a procedure for determining the kinetic parameters of ions (velocity V_i and temperature T_i) by the electron saturation current measured using the IPS.

Mathematical model of current collection by the IPS in a supersonic flow of dissociated rarefied plasma is based on asymptotic formulas for the ion and electron currents on a long transversely oriented cylindrical electrode [4, 5]. The dimensionless total current per cylinder is

$$\bar{I}_c(\varphi) = \bar{I}_e(\varphi) + \bar{I}_i(\varphi) \,, \tag{1}$$

$$\bar{I}_e(\varphi) = \begin{cases} 2/\sqrt{\pi} \cdot \sqrt{\pi/4 + \varphi}, & \varphi > 0; \\ \exp(\varphi), & \varphi \le 0 \end{cases} ,$$

$$\bar{I}_i(\varphi) = -(1 + 0{,}414\,\eta)\sqrt{\frac{\mu}{\beta}} \begin{cases} \sqrt{2/\pi}\,\exp\left(-\beta\varphi + S_i^{\,2}\right), & \varphi \ge S_i^{\,2}/\beta; \\ 2/\sqrt{\pi}\,\sqrt{1/2 + S_i^{\,2} - \beta\varphi}, & \varphi < S_i^{\,2}/\beta \end{cases} ,$$

where $\bar{I}_c$, $\bar{I}_e$, $\bar{I}_i$ are the total, electron and ion currents, respectively, normalized by the thermal electron current on a cylinder $I_{e,0}$, $\varphi = eU/kT_e$ is the dimensionless electric potential (U stands for the dimensional potential) of the electrode relative to the unperturbed plasma, e is the elementary charge, k is the Boltzmann constant, T_e is the electron temperature, $\mu = m_e/m_i$ is charged particles mass ratio, $\beta = T_e/T_i$ is charged particles temperature ratio, $S_i = V_i/u_i$ is ion velocity ratio (u_i stands for molecular ions thermal velocity).

The electrodes areas ratio $S_s = S_{cp}/S_p >> 1$ is the important geometric parameter of the IPS, which determines the balance of currents to the electrodes. The reference electrode is always at a negative equilibrium potential U_{cp} relative to the plasma. Probe potential relative to undisturbed plasma is $U_p = U_{iz} + U_{cp}$, where U_{iz} is the potential of the probe relative to the reference electrode (bias potential). The equilibrium potential $U_{cp} = U_{cp}(U_{iz})$ is found from the current balance equation for the reference electrode [4]. In dimensionless variables, the calculation of the current-voltage characteristic (CVC) of the probe $\bar{I}_p(\varphi_{iz})$ taking into account relations (1) is represented by the following system of nonlinear equations

$$\bar{I}_p(\varphi_{iz}) = \bar{I}_c(\varphi_{iz} + \varphi_{cp}),$$

$$S_s \cdot \bar{I}_c(\varphi_{cp}) + \bar{I}_c(\varphi_{iz} + \varphi_{cp}) = 0 \,. \tag{2}$$

Relations (1), (2) determine the parametric representation of the CVC of the “probe – plasma – reference electrode” system with the dimensionless parameters η, μ, β, S_i, S_s, φ_{iz}.

In the electronic region of the CVC at sufficiently large bias potential U_{iz}, the probe potential satisfies $U_p \ge m_i V_i^2/2e$. The equilibrium potential of the reference electrode always satisfies the relation $U_{cp} < 0 < m_i V_i^2 / 2e$. In this case, the current balance equation (2) resolves analytically, and for the CVC $\bar{I}_p(\varphi_{iz})$ an asymptotic solution is obtained [4]:

$$\bar{I}_p(\varphi_{iz}) \approx \frac{2}{\sqrt{\pi}} \cdot \sqrt{\frac{S_s^2 \mu (1+0{,}414\eta)^2}{S_s^2 \mu (1+0{,}414\eta)^2 + 1}} \cdot \sqrt{\frac{1/2 + S_i^2}{\beta} + \frac{\pi}{4} + \varphi_{iz}} \ . \tag{3}$$

In solution (3), the bias potential is restricted by $\varphi_{iz}^{\min} < \varphi_{iz} < \varphi_{iz}^{\max}$, the values $\varphi_{iz}^{\min}$, $\varphi_{iz}^{\max}$ for diagnosing plasma in the core area of the jet are defined in [5].

The inverse problem is to determine plasma parameters (that are represented by the aforementioned mathematical model parameters) using measured probe current $I_p(U_{iz})$ at certain geometric parameters of the IPS. Analysis of the asymptotic solution (3) shows that the IPS's electron saturation current depends on the ions velocity S_i and plasma nonisothermality β. We use this circumstance to estimate the kinetic parameters of ions by probe measurements in the electron saturation region, where the current significantly exceeds that in the ion region of the CVC.

Performing straightforward transformations in (3), we obtain the following relation between dimensional potentials and currents:

$$\frac{I_p^2(U_{iz})}{I_p^2(U_{iz}+dU) - I_p^2(U_{iz})} \approx \frac{\left[\left(1/2 + S_i^2\right)/\beta + \pi/4\right] kT_e/e + U_{iz}}{dU} \ , \tag{4}$$

where dU is the increment to the bias potential U_{iz}. Both U_{iz} and $U_{iz} + dU$ must belong to the range of applicability of solution (3):

$$U_{iz} \in \left[\varphi_{iz}^{\min} kT_e/e, \varphi_{iz}^{\max} kT_e/e\right]. \tag{5}$$

Substituting expressions for parameters S_i and β into (4), we obtain a calculation formula for estimating the kinetic parameters of plasma:

$$\frac{m_i V_i^2}{2e} + \frac{kT_i}{2e} + \frac{\pi k T_e}{4e} \approx \frac{I_p^2(U_{iz}) \cdot dU}{I_p^2(U_{iz}+dU) - I_p^2(U_{iz})} - U_{iz} \,. \tag{6}$$

The left-hand side of (6) characterizes the average kinetic energy of charged particles (in electronvolts): the first term $m_i V_i^2 / 2e$ characterizes the average kinetic energy of ions mass motion, the second term $kT_i/2e$ characterizes the average kinetic energy of the ions thermal motion, the third term $\pi k T_e / 4e$ characterizes the average kinetic energy of the electrons thermal motion.

The right-hand side of (6) contains only the dimensional values of probe current and bias potentials in the electron saturation region and it doesn't depend explicitly neither on the plasma parameters nor on the IPS's geometric parameters. As there is no such calculation formula in the theory of a single Langmuir probe [3], the proposed method of plasma diagnostics based on the IPS appears to be comparatively more informative.

Let us introduce the following quantities:

$$K=\frac{m_iV_i^2}{2}+\frac{kT_i}{2}+\frac{\pi kT_e}{4}\,,\;K_i=\frac{m_iV_i^2}{2}+\frac{kT_i}{2}\,,$$

$$D_K=\frac{I_p^{\,2}(U_{iz})\cdot dU}{I_p^{\,2}(U_{iz}+dU)-I_p^{\,2}(U_{iz})}-U_{iz}\,,$$

where I_p is the probe current of the IPS with the ratio of electrode areas S_s, U_{iz} and $U_{iz}+dU$ are the bias potentials in the range of (5) (assuming $dU>0$). Within the framework of the considered mathematical model of current collection (1), (2), the quantity K stands for the average kinetic energy of charged particles, and the quantity K_i is the average kinetic energy of ions in a gas-discharge plasma jet.

From formula (6) it follows that $K/e\approx D_K$, $K_i/e\approx D_K-K_e/e$. Thus, D_K it is a measurable quantity that estimates, within the potential range (5) where (3) is applicable, the average kinetic energy of charged plasma particles. Note that D_K is always positive and in the stationary plasma flow within the framework of the considered current collection model it does not depend on the bias potentials during the measurement. The values of D_K are straightforwardly obtained by the standard method of processing the results of probe current I_p measured ny the IPS with certain electrodes areas ratio S_s at different bias potentials in the electron saturation region (5).

Let us consider the influence of the IPS's electrodes areas ratio and the errors in measuring probe current and bias potential on the reliability of the determination of the plasma kinetic parameters using (6).

Methodological error of the calculation formula (6) within the framework of the mathematical model of current collection (1), (2) is estimated by calculating D_K through the currents $I_p(U_{iz})$ found from the solution of problem (2) and comparing the result with K/e.

Fig. 1 shows the dependence of the relative error $\bar{\varepsilon}_{D_K}=\left(\overline{D}_K-D_K\right)/D_K$ on the bias potential U_{iz} (in volts). Here, $\overline{D}_K$ is the value of D_K at probe current $I_p(U_{iz})$ calculated by the mathematical model (1), (2) for various dU and S_s. Numbers on Fig. 1 correspond to various S_s as follows: S_s = 100 (1), 200 (2), 300 (3), 400 (4).

In Fig. 1, a) dotted curves correspond to dU = 5 V, thin dashed curve: dU = 10 V, thin solid curve: dU = 20 V, thick dashed curve: dU = 50 V, thick solid curve: dU = 100 V. In Fig. 1, b) the solid curve corresponds to dU = 10 V, the dashed curve: dU = 50 V. Calculations were performed for nitrogen at $n_e=1.0\cdot 10^{14}\ m^{-3}$, $T_e=2.5\cdot 10^4$ K, $\eta=0.5$, $S_i=4$, $\beta=4.2$, that correspond to the laboratory plasma parameters which is used to model the ionosphere [2].

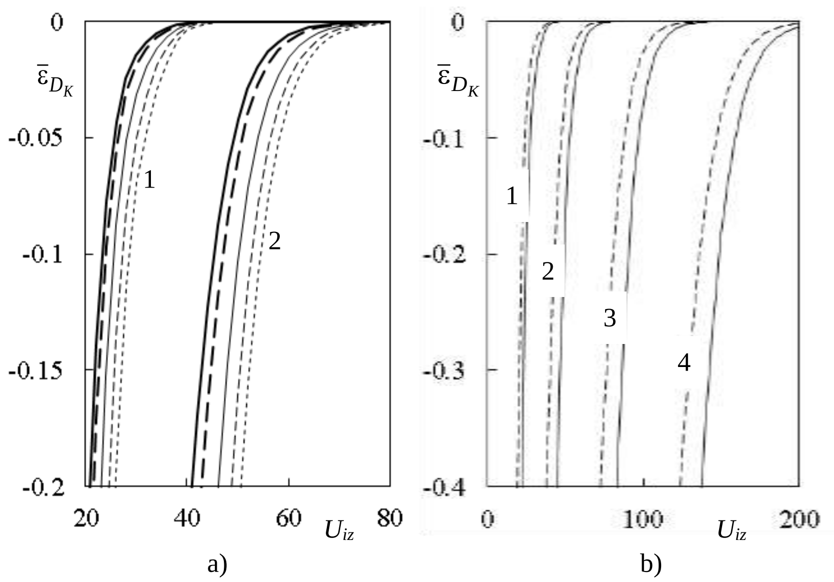

Fig. 1

The results presented in Fig. 1, a) show that as the variation of bias potential dU increases, the methodological error of the calculation formula (6) decreases: a change in dU from 10 V to 50 V shifts the error curve $\bar{\varepsilon}_{D_K}$ towards lower bias potentials by ~5 V. For IPS with S_s =100, the methodological error does not exceed 2% at $dU \geq 50$ and U_{iz} > 30 V, and 1% at $dU \geq 10$ and U_{iz} > 35 V.

Analysis of results presented in Fig. 1, b) shows that an increase in the electrode areas ratio S_s shifts the applicable range of (6) towards high potentials U_{iz} and at $S_s > 400$ formula (6) becomes practically inapplicable.

Probe measurement errors. Let's consider the influence of current and voltage measurement errors on the D_K determination error. When the IPS with electrodes areas ratio of S_s measures the bias potential U_{iz} and corresponding probe current $I_p(U_{iz})$, due to measurement errors we obtain approximate values:

$$\tilde{U}_{iz} = U_{iz}(1+\tilde{\varepsilon}_U),\ \tilde{I}_p(\tilde{U}_{iz}) = I_p(\tilde{U}_{iz})(1+\tilde{\varepsilon}_I), \tag{7}$$

where $\tilde{\varepsilon}_U$, $\tilde{\varepsilon}_I$ are random values on $[-\varepsilon_U, \varepsilon_U]$, $[-\varepsilon_I, \varepsilon_I]$, respectively; ε_U, ε_I are maximum relative measurement errors (ε_U, ε_I > 0). Then, within the framework of the considered mathematical model of the IPS current collection, it follows from (7) [5]:

$$\tilde{I}_p(\tilde{U}_{iz}) = I_p(U_{iz})\left(1+\tilde{\varepsilon}_I + \frac{U_{iz}}{D_K + U_{iz}}\tilde{\varepsilon}_U\right).$$

Substituting approximate values $\tilde{U}_{iz}$, $\tilde{I}_p(\tilde{U}_{iz})$ into expression for D_K, neglecting the second order small members, after the straighforward transformations, taking into account (4) and the accepted notation, we obtain the following estimate:

$$\left|\frac{\tilde{D}_K - D_K}{D_K}\right| \le \varepsilon_{D_K} ,$$

$$\varepsilon_{D_K} \approx \left(\frac{U_{iz}}{D_K}+1\right)\left(\frac{D_K}{dU}+\frac{U_{iz}}{dU}+1\right)\frac{4\varepsilon_I+\left(\frac{U_{iz}}{D_K+U_{iz}}+\frac{U_{iz}+dU}{D_K+U_{iz}+dU}\right)\varepsilon_U}{1-2\left(2\frac{D_K+U_{iz}}{dU}+1\right)\varepsilon_I-2\frac{2U_{iz}+dU}{dU}\varepsilon_U} , \quad (8)$$

where $\tilde{D}_K$ is the value of D_K calculated using the measured values (7), and ε_{D_K} is the maximum relative error in determining D_K.

Fig. 2 illustrates the influence of potential increment dU, bias potential U_{iz} and relative errors in measuring currents ε_I and voltages ε_U on the maximum relative error ε_{D_K} of determining the average kinetic energy of charged plasma particles using formula (6). Dependences of ε_{D_K} on the potential increment dU (in volts) at bias potentials U_{iz}=30 V (solid curves) and U_{iz}=40 V (dashed curves) for various ε_I at ε_U=0 are shown in Fig. 2, a) and for various ε_U at ε_I=0 – in Fig. 2, b). Curves in Fig. 2, a), b) correspond to the following values of current (a) and voltage (b) measurement errors: 0.001 (1), 0.005 (2), 0.01 (3), 0.02 (4).

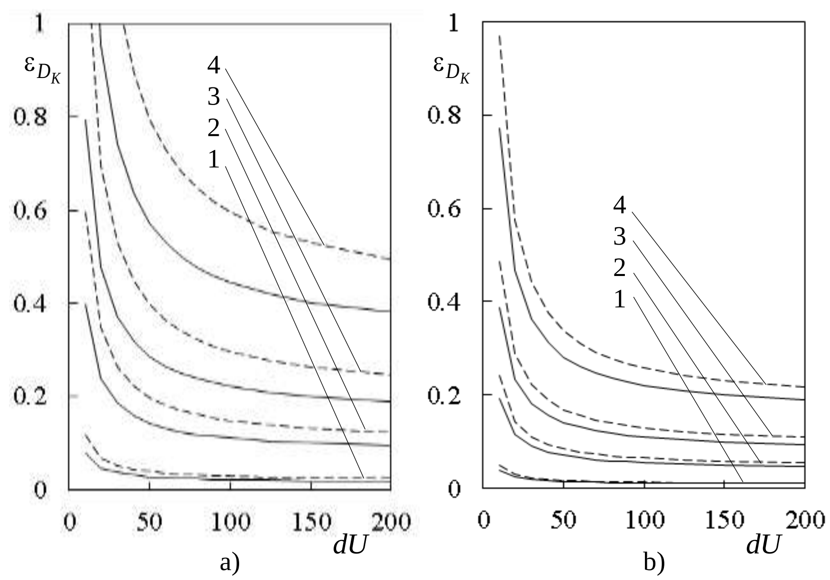

Fig. 2

In relation (8), the relative error does not depend explicitly on the electrodes areas ratio S_s. However, the total error includes the methodological error of formula (6), which depends on S_s, as shown in Fig. 1. Data in Fig. 2 are obtained for bias potentials U_{iz}≤40 V, that correspond to measurements by IPS with $S_s \approx 100$.

Analysing the results presented in Fig. 2, we note that the error ε_{D_K} decreases monotonically as bias potential U_{iz} decreases and bias potential increment dU increases. At dU > 100 V, its further increasing doesn't lead to a significant error ε_{D_K} decreasing.

To adequately determine the average kinetic energy of charged plasma particles, the maximum relative error in measuring the probe current and bias potential shouldn't exceed ~1 %. At U_{iz} =30 V, dU > 50 V, $\varepsilon_I \le 0.5$ % and $\varepsilon_U \le 0.5$ % the error ε_{D_K} <22 %, and ε_{D_K} <28 % at $dU \ge 100$ V, $\varepsilon_I \le 1$ % and $\varepsilon_U \le 0.5$ %. At the same time, the methodological error in determining the average kinetic energy of charged plasma particles by formula (6) accordingly to the data in Fig. 1 for S_s =100 is less than 2 %.

Expanding the right-hand side of (8) into a series in ε_I, ε_U and keeping the values of the 1st order of smallness, taking into account the obvious $\frac{U_{iz}}{D_K + U_{iz}} + \frac{U_{iz} + dU}{D_K + U_{iz} + dU} < 2$, we obtain a simple but sufficient for practical use estimate of the maximum relative error:

$$\left|\frac{\tilde{D}_K - D_K}{D_K}\right| \le \varepsilon_{D_K} \approx 2\left(\frac{U_{iz}}{D_K} + 1\right)\left(\frac{D_K}{dU} + \frac{U_{iz}}{dU} + 1\right) \cdot \left(2\varepsilon_I + \varepsilon_U\right), \qquad (9)$$

As a result of the analysis of the influence of measuring errors on the ε_{D_K} error, as well as the influence of S_s and U_{iz} on the methodological error of formula (6), we conclude that to adequately estimate the kinetic parameters of charged particles by the measurements of D_K, it is reasonable to take S_s of about 100, U_{iz} less than about 50 V and dU from 50 to 100 V.

Kinetic parameters of plasma. The quantities K and K_i that characterize the kinetic energy of charged particles don't depend on probe measurements and they are determined by the local parameters of the plasma. In the working region of a supersonic jet, the values of K, K_i are close to constants and are estimated through D_K using formula (6).

Thus, having determined $\tilde{D}_K$ from probe measurements, we obtain from (6), (9) an estimate of the average kinetic energy K of charged particles in the working region of a supersonic plasma jet:

$$\tilde{K} \approx e\tilde{D}_K, \quad \left|\frac{\tilde{K} - K}{K}\right| \le \varepsilon_K = \varepsilon_{D_K},$$

where $\tilde{K}$ is the approximate value of K calculated from the results of probe measurements, ε_K is the relative error in determining K, ε_{D_K} is estimated in (9).

It was shown in [6] that the accuracy of determining electrons temperature in a supersonic jet of collisionless plasma of a diatomic gas using an IPS is comparable to the accuracy of measurements with a single cylindrical probe. Let the electron temperature $\tilde{T}_e$ be known with a maximum relative error ε_{T_e}. Then the average kinetic energy of ions K_i is determined as follows:

$$\tilde{K}_i \approx e\tilde{D}_K - \pi k\tilde{T}_e/4, \quad \left|\frac{\tilde{K}_i - K_i}{K_i}\right| \le \varepsilon_{K_i} \approx \varepsilon_{D_K}\frac{K}{K_i} + \varepsilon_{T_e}\frac{\pi k T_e/4}{K_i}, \qquad (10)$$

where $\tilde{K}_i$ is the value of K_i calculated from the results of probe measurements, and ε_{K_i} is the relative error in determining K_i.

It is impossible to separate the contribution of the directional and thermal motion of ions to the value of K_i within the framework of the considered model of IPS's current collection. To do this, the special experiments to determine either ion temperature T_i or mass velocity V_i are necessary to carry out [3, 8].

If the ion temperature $\tilde{T}_i$ is known with a maximum relative error ε_{T_i}, then the mass velocity V_i of molecular ions motion is determined as follows:

$$\tilde{V}_i = \sqrt{2\left(\tilde{K}_i - k\tilde{T}_i/2\right)/m_i} \ ,$$

$$\left|\frac{\tilde{V}_i - V_i}{V_i}\right| \le \varepsilon_{V_i} \approx \frac{1}{2}\left(\varepsilon_{D_K}\frac{K}{m_i V_i^2/2} + \varepsilon_{T_e}\frac{\pi k T_e/4}{m_i V_i^2/2} + \varepsilon_{T_i}\frac{kT_i/2}{m_i V_i^2/2}\right), \quad (11)$$

where $\tilde{V}_i$ is the value of V_i calculated from the results of probe measurements, and ε_{V_i} is the relative error in determining V_i. According to the accepted assumption, the velocity of atomic ions is $V_{i,1} = \sqrt{2}\ V_i$.

A priori estimates can be obtained from the results of experimental studies of a gas-discharge plasma source with ion acceleration in the electric field of the jet [1, 9]. In the working region of the jet, the plasma parameters at an electron temperature of about 2 eV correspond to the following values: $\pi k T_e/4e \approx 1.7$ eV, $m_i V_i^2/2e \approx 8.75$ eV, $kT_i/2e \approx 0.25$ eV. At such considered quantities, for the error of determining K_i from (10) and V_i from (11), we obtain a priori estimates:

$$\left|\frac{\tilde{K}_i - K_i}{K_i}\right| \le \varepsilon_{K_i} \approx 1.19\varepsilon_{D_K} + 0.19\varepsilon_{T_e} \ ,$$

$$\left|\frac{\tilde{V}_i - V_i}{V_i}\right| \le \varepsilon_{V_i} \approx 0.62\varepsilon_{D_K} + 0.01\varepsilon_{T_e} + 0.014\varepsilon_{T_i} \ .$$

As we can see, the reliability of determining the mass velocity of ions is quite high and it is characterized mainly by the level of D_K determination error.

If there is reliable information about the mass speed $\tilde{V}_i$ of the supersonic ion flow, then ion temperature T_i in the working area of the jet is estimated as follows:

$$\tilde{T}_i = 2\left(\tilde{K}_i - m_i\tilde{V}_i^2/2\right)/k \ , \quad \left|\frac{\tilde{T}_i - T_i}{T_i}\right| \le \varepsilon_{T_i} \approx 43\varepsilon_{D_K} + 7\varepsilon_{T_e} + 70\varepsilon_{V_i} \ ,$$

where $\tilde{T}_i$ is the value of T_i calculated from the results of probe measurements, ε_{T_i} is the relative error in determining T_i, and ε_{V_i} is the relative error in determining V_i. Large coefficients in the error estimate ε_{T_i} mean that using the results of the

IPS probe measurements, similarly to the case of a single cylindrical probe, the ion temperature T_i can only be estimated by an order of magnitude.

Conclusions. A procedure based on the electric current measurements using the insulated probe system with transversely oriented cylindrical electrodes is developed for determining kinetic parameters of charged particles in a supersonic jet of a gas-discharge plasma source. Probe measurements results obtained using the IPS in plasma jet of the gas-discharge source is shown theoretically to be more informative than that of the single cylindrical Langmuir probe.

Within the framework of the accepted assumptions, a new relationship between the temperature, mass velocity of ions, the temperature of the electrons and probe currents measured by the IPS in the electron saturation regime is obtained. Numerical and analytical estimates of the errors of determining the plasma kinetic parameters are obtained depending on the geometric parameters of the probe system, the accuracy of measuring probe current and bias potential relative to the potential of the reference electrode.

It has been shown that in order to adequately estimate the average kinetic energy and mass velocity of ions in a supersonic gas-discharge plasma jet, it is reasonable to choose an electrode areas ratio of about 100 and measure, electric currents at the bias potentials of less than 50 V with increment of about (50 – 100) V The ion temperature by the results of IPS's measurements, as in the case of a single Langmuir probe, can only be estimated by an order of magnitude.

The obtained results can be used in the diagnostics of laboratory plasma of a gas-discharge source.

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