

## DETERMINATION OF THE ELECTRON TEMPERATURE IN A SUPERSONIC JET OF A GAS-DISCHARGE SOURCE FROM CURRENT MEASUREMENTS BY AN ISOLATED PROBE SYSTEM

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Метою роботи є обґрунтування можливості застосування класичної процедури визначення температури електронів для діагностики надзвукового струменя беззіттовхувальної плазми двоатомного газу за вольтамперною характеристикою ізольованої зондової системи. Зондова система являє собою поперечно обтічний циліндричний зонд і опорний електрод, складений з декількох циліндрів. Відношення площі опорного електроду, що збирає струм, до площі зонду довільно і може бути істотно меншим вимог теорії одиночного зонда.

На основі побудованої раніше математичної моделі збирання струмів, що включає розрахунок рівноважного потенціалу опорного електроду при зміні напруги зсуву зонда, розроблено процедуру відновлення температури електронів за результатами вимірювань зондових струмів у струмені газорозрядного джерела лабораторної дисоційованої плазми. Знайдено апроксимацію плаваючого потенціалу ізольованої зондової системи в сильно нерівноважній плазмі струменя газорозрядного джерела, що дозволяє за апіорною інформацією про параметри плазми локалізувати границі перехідної області вольтамперної характеристики. Отримано формулу екстраполяції в перехідну область вольтамперної характеристики функціональної залежності іонного зондового струму від потенціалу зсуву.

У рамках прийнятої математичної моделі збирання струмів заряджених частинок плазми виконаний числовий аналіз методичної погрішності процедури визначення температури електронів. Отримано кількісні характеристики впливу геометричних параметрів ізольованої зондової системи на методичну погрішність. Числове моделювання впливу погрішностей вимірювань зондових струмів показало, що в рамках прийнятої моделі точність відновлення температури електронів при використанні ізольованої зондової системи порівнянна з точністю вимірювань одиночним циліндричним зондом.

Отримані результати можуть бути використані в діагностиці лабораторної плазми газорозрядного джерела.

**Ключові слова:** струмінь беззіттовхувальної плазми, сильна нерівноважність, двоохортні іони, ізольована зондова система, процедура визначення температури електронів, оцінки методичної погрішності.

The aim of this work is to substantiate the possibility of using the classical procedure for determining the electron temperature for diagnosing a supersonic jet of a collisionless plasma of a diatomic gas using the current-voltage characteristic of an insulated probe system. The probe system consists of a cylindrical probe and a reference electrode composed of several cylinders, all placed transversely in the plasma flow. The ratio of the current-collecting surface area of the reference electrode to the area of the probe is arbitrary and can be significantly less than required by the theory of a single probe.

Based on a previously constructed mathematical model of current collection, which includes the calculation of the equilibrium potential of the reference electrode as a function of the probe bias voltage, a procedure is developed for determining the electron temperature by measuring the probe currents in a jet of a gas-discharge source of a laboratory dissociated plasma. An approximation of the floating potential of the insulated probe system in a strongly nonequilibrium plasma of a gas-discharge source jet is found, which allows one to determine the boundaries of the transition region of the current-voltage characteristic using a priori information on the plasma parameters. A formula is obtained for extrapolating the ion probe current vs. bias potential relationship into the transition region of the current-voltage characteristic.

Within the framework of the adopted mathematical model of charged plasma particle collection, a numerical analysis of the method error of the electron temperature determination procedure is performed. Quantitative characteristics of the effect of the insulated probe system geometry on the method error are obtained. A numerical simulation of the effect of the probe current measurement errors showed that, within the framework of the adopted model, the accuracy of determining the electron temperature using the insulated probe system is comparable with the accuracy of measurements with a single cylindrical probe.

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

**Keywords:** collisionless plasma jet, strong nonequilibrium, two-species ions, insulated probe system, electron temperature determination procedure, method error estimates.

**Introduction.** Until now, the gas-discharge sources (GDS) of plasma [1] have been widely used in the complex laboratory modeling of the magnetogasdynamic interaction of on-board instruments and structural elements of spacecraft with ion-

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ospheric plasma. Therefore, increasing the information content and accuracy of laboratory plasma diagnostics is an important part of the physical modeling of environment in orbit.

This article is a continuation of works [2, 3] on the development of a procedure for determining the parameters of charged particles in a supersonic GDS jet of a collisionless plasma by the results of measurements of the current collected by an isolated probe system (IPS) with cylindrical electrodes oriented transversely to the plasma flow. Under the condition that the ions are accelerated in the electric field of the source jet, an asymptotic solution for the probe current in the electron saturation regime is obtained for the dissociated plasma of a diatomic working gas. Relationships between the collected probe currents for various probe and reference electrode surface area ratio and the degree of ion dissociation and electron density are obtained.

In this article, the procedure for obtaining the electron temperature in a plasma source jet by the probe currents measured with the IPS with cylindrical electrodes is considered. The influence of the geometrical parameters of the probe system on the reliability of obtaining the electron temperature is studied.

**Problem formulation and mathematical model** for collecting currents of IPS with transversely oriented cylindrical electrodes in a supersonic GDS jet of a diatomic gas are described in [3].

It is assumed that the plasma is Maxwellian, collisionless, quasi-neutral, there is no magnetic field, the temperatures of atomic and molecular ions are equal ( $T_{i,1} = T_{i,2} = T_i$ ), the velocities of atomic  $V_{i,1}$  and molecular  $V_{i,2}$  ions satisfy the relation  $V_{i,1}/V_{i,2} = \sqrt{2}$ . The degree of dissociation of ions in the jet is characterized by the parameter  $\eta = n_{i,1}/n_e$ , where  $n_{i,1}$  is the density of atomic ions and  $n_e$  is the density of electrons.

Measuring electrode (probe) and reference electrodes are electrically isolated from the body of the vacuum chamber. The reference electrode is a series of parallel cylinders, each of which can be connected or disconnected from the measurement electrical circuit. Let's consider the electrode base radii to be much smaller than their length, therefore, the asymptotic Langmuir solution for the ion current to a cylinder transversely placed into the flow is applicable [2], the end surfaces of the electrodes to be isolated from the plasma, the electrostatic and gas-dynamic influence of the electrodes on each other in the plasma to be weak, and there are no emission currents from the electrode surfaces. The main geometrical parameter of the IPS is the ratio of the electrode areas  $S_s = S_{cp}/S_p$ , where  $S_{cp}$  is the area of the current-collecting surface of the reference electrode,  $S_p$  is the area of the probe surface ( $S_p \ll S_{cp}$ ).

The numerical representation of the current-voltage characteristic (CVC) of the IPS is given in [2, 3]. In the ion-collection and transition parts of the CVC at negative potentials  $U_p$  relative to the unperturbed plasma potential, in dimensional form, the ion  $I_i$  and electron  $I_e$  currents to the cylindrical probe are determined by the relations:

$$I_i(U_p) = -\frac{e}{\pi} \sqrt{\frac{2e}{m_i}} n_e S_c (1 + 0.414\eta) \sqrt{\frac{kT_i}{2e} + \frac{m_i V_i^2}{2e} - U_p}, \quad (1)$$

$$I_e(U_p) = en_e S_c \sqrt{\frac{kT_e}{2\pi m_e}} \exp\left(\frac{eU_p}{kT_e}\right), \quad (2)$$

where  $e$  is the elementary charge,  $m_i$  is the mass of molecular ions,  $S_c$  is the area of the cylindrical electrode,  $k$  is the Boltzmann constant,  $V_i$  is the mass velocity of molecular ions,  $m_e$  is the mass and  $T_e$  is the temperature of electrons.

The probe potential relative to the unperturbed plasma potential is  $U_p = U_{iz} + U_{cp}$ , where  $U_{iz}$  is the probe potential relative to the reference electrode,  $U_{cp}$  is the equilibrium potential of the reference electrode relative to the unperturbed plasma. This potential  $U_{cp} = U_{cp}(U_{iz})$  is found from the current balance equation for the reference electrode [3].

**The direct problem of probe measurements** is to calculate the CVC of the probe, i.e., the dependence of the probe current  $I_p$  on the bias potential  $U_{iz}$  for given parameters of the unperturbed plasma and the IPS. For the CVC  $I_p(U_{iz})$  in the electron saturation regime at sufficiently high positive bias potential  $U_{iz}$ , an asymptotic solution was obtained in [2], which made it possible to obtain calculation formulas for determining the degree of diatomic ions dissociation  $\eta$  and the electron density  $n_e$  from measurements of electron saturation current. In a GDS plasma jet, the asymptotic solution is applicable for bias potentials from the interval

$$\phi_{iz}^{\min} \cdot \frac{kT_e}{e} < U_{iz} < \phi_{iz}^{\max} \cdot \frac{kT_e}{e}, \quad (3)$$

where  $\phi_{iz}^{\min}$ ,  $\phi_{iz}^{\max}$  are defined in [3].

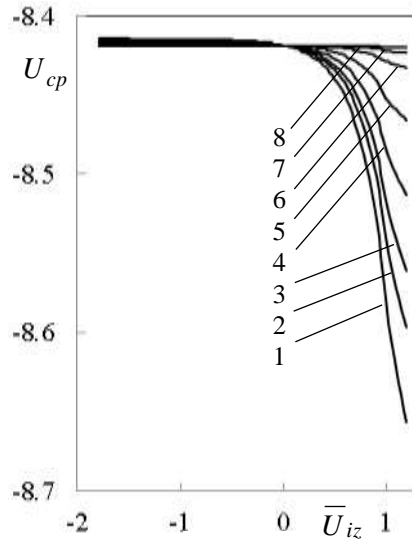


Fig. 1

Similarly to the case of a single cylindrical probe ( $S_s \rightarrow \infty$ ), the CVC of the IPS can be conditionally divided into three characteristic parts: the ion saturation region at  $U_{iz} < U_{fl}$ , the electron saturation region at  $U_{iz} > -U_{fl}$ , and the transition region  $U_{fl} < U_{iz} < -U_{fl}$ . Here,  $U_{fl}$  is the floating potential of the IPS (potential of the reference electrode  $U_{cp}$  at  $U_{iz} = 0$ ). The CVC of the IPS differs from the CVC of a single cylindrical probe most strongly in the electron saturation region [3]. The ion region of the CVC of the IPS with the ratio of the electrodes surface areas  $S_s > 20$  practically coincides with the

CVC of a single probe, for which the potential of the reference electrode relative to the plasma potential is constant.

Fig. 1 shows the dependences of the equilibrium potential  $U_{cp}$  (in volts) on the dimensionless bias potential  $\bar{U}_{iz} = U_{iz}/|U_{fl}|$  in the transition region of the IPS CVC at various area ratios:  $S_s = 600$  (1), 800 (2), 1000 (3), 1500 (4), 3000 (5),  $10^4$  (6),  $3 \cdot 10^4$  (7),  $10^5$  (8). The calculations were performed for nitrogen at  $n_e = 1.0 \cdot 10^{14}/\text{m}^3$ ,  $\eta = 0.5$ ,  $T_e = 2.5 \cdot 10^4$  K,  $T_e/T_i = 4.2$ ,  $V_i = 1.0 \cdot 10^4$  m/s, that correspond to laboratory plasma used in modeling the ionosphere [2]. The floating potential in this case is  $U_{fl} \approx -8.42$  V.

As we notice, even at  $S_s = 10^4$  on the boundary of the transition and electron regions of the CVC, the equilibrium potential of the reference electrode differs a lot from the constant one. At negative  $U_{iz}$  the potential of the reference electrode is almost constant.

For the plasma of the GDS jet, the floating potential of the IPS with sufficient accuracy for practical application is estimated:

$$U_{fl} \approx \ln \left( \frac{2}{\sqrt{\pi}} \sqrt{\frac{2}{2-\eta}} \sqrt{\frac{m_e V_i^2}{2kT_e}} - \mu(1+0.414\eta) \ln \left( \frac{2}{\sqrt{2-\eta}} \cdot \frac{\sqrt{m_e V_i}}{\sqrt{\pi k T_e}} \right) \right) \cdot \frac{kT_e}{e},$$

where  $\mu = m_e/m_i$  is the ratio of the masses of electrons and molecular ions.

In the ion region at  $U_{iz} < U_{fl}$ , the probe current of the IPS is mostly the ion current (1):

$$I_p(U_{iz}) \approx -\frac{e}{\pi} \sqrt{\frac{2e}{m_i}} n_e S_p (1+0.414\eta) \sqrt{\frac{kT_i}{2e} + \frac{m_i V_i^2}{2e}} - U_{cp} - U_{iz}. \quad (4)$$

**Reverse problem.** In [3], a procedure is developed for determining the degree of dissociation  $\eta$  of diatomic ions and the electron density  $n_e$  from measurements of the probe current in the electronic region of the CVC of the IPS. Calculation formulas and estimates of the error in determining the parameters  $\eta$  and  $n_e$  are obtained. Let's introduce quantities:

$$D_\eta = \frac{1}{S_{s,2}^2} \frac{[I_{p,1}^*(U_{iz})]^2 \cdot p_s^2 - [I_{p,2}^*(U_{iz})]^2}{[I_{p,2}^*(U_{iz})]^2 - [I_{p,1}^*(U_{iz})]^2}, \quad D_n = \frac{[I_p^*(U_{iz2})]^2 - [I_p^*(U_{iz1})]^2}{U_{iz2} - U_{iz1}}, \quad (5)$$

where  $I_{p,1}^*$ ,  $I_{p,2}^*$ ,  $I_p^*$  stand for the probe currents at electrodes area ratios  $S_{s,1}$ ,  $S_{s,2}$  and  $S_s^*$ , respectively;  $p_s = S_{s,2}/S_{s,1} > 1$ ;  $U_{iz}$ ,  $U_{iz1}$ ,  $U_{iz2}$  are bias potentials from the range (3) ( $U_{iz1} < U_{iz2}$ ).

Note that, within the framework of the accepted mathematical model,  $D_\eta$ ,  $D_n$  are always positive and constant for a specific stationary plasma flow (they do not depend on the bias potentials during measurement). The values of  $D_\eta$ ,  $D_n$  are

found by substitution in (5) the results of current measurements at different bias potentials in the electron saturation region (3) and at different values of the electrode area ratio [3].

Knowing the values (5), the calculation formulas for determining the degree of ion dissociation and electron density writes as follows:

$$\eta \approx 2.414 \left( \sqrt{D_\eta / \mu} - 1 \right), \quad (6)$$

$$n_e \approx \frac{\pi}{e S_p} \cdot \sqrt{\frac{m_e}{2e}} \cdot \sqrt{\left[ \left( S_s^* D_\eta \right)^{-1} + 1 \right] D_n}. \quad (7)$$

**Electron temperature** is traditionally determined from the CVC of a single cylindrical probe, the reference electrode to which in the GDS jet plasma is the inner surface of the walls of the vacuum chamber [4].

Fig. 2 shows the dependence of probe currents on the bias potential  $\bar{U}_{iz} = U_{iz} / |U_{fl}|$  in the transition region of the CVC of the IPS at the electrode area ratio of  $S_s = 400$ . Here, curve 1 represents the total probe current  $I_p$ , 2 - the electron current  $I_i$ , and 3 - the ion current  $I_e$ . For a single cylindrical probe, the dependence of the collected currents on the bias potential  $U_{iz} / U_{pl}$ , where  $U_{pl}$  is the potential of plasma (environment) with respect to the walls of the vacuum chamber, does not qualitatively differ from that shown in Fig. 2, since the physical processes of the “plasma-probe” interaction are the same for the IPS and a single cylindrical probe.

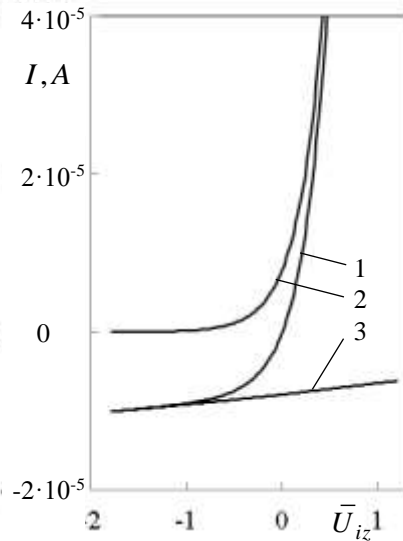


Fig. 2

As the bias potential increases and passes from ion saturation to the transition region of the CVC, the electron current begins to contribute to the total probe current. At a zero bias potential  $U_{iz}$ , the electron current reaches the level of the ion current to the probe ( $I_p = 0$ ), a further increase in  $U_{iz}$  leads to a significant dominance of the electron current ( $I_i \ll I_e$ ). The classical procedure for determining the electron temperature from the CVC of a single cylindrical probe consists of the following steps [5, 6]:

- 1) Measurement of the CVC  $I_p^{msr}(U_{iz})$ .

Here, we need to pay special attention to measuring in the transition region of the CVC, where, as is known, the level of plasma noise can exceed the level of the probe current.

- 2) Estimation of the electron current  $I_e(U_{iz})$  in the transition region of the CVC. In this step, the ion current is extrapolated to the transition region  $I_i^{extr}(U_{iz})$

using the ion saturation region of the CVC, and the electron current is estimated by the relation  $I_e(U_{iz}) \approx I_p^{msr}(U_{iz}) - I_i^{extr}(U_{iz})$ .

3) Determination of the electron temperature by the calculation formula:

$$T_e \approx \frac{e}{k} \left( \frac{d}{dU_{iz}} \ln[I_e(U_{iz})] \right)^{-1}.$$

A series of methods for extrapolating the ion current and differentiating the experimentally obtained function  $\ln[I_e(U_{iz})]$  is in practical use currently.

Let's apply this procedure to the CVC of IPS. We extrapolate the ion current using relation (4) for the probe current in the ion region ( $U_{iz} < U_{fl}$ ) assuming that the equilibrium potential  $U_{cp}$  doesn't change significantly for specific measurement case in the transition region of the CVC. For a specific measurement of the probe current  $I_p^{**}(U_{iz}^{**})$  in the ion region  $U_{iz}^{**} < U_{fl}$  at the electrodes areas ratio of  $S_s^{**}$ , from (4) we obtain

$$I_p^{**}(U_{iz}^{**}) = -\frac{e}{\pi} \sqrt{\frac{2e}{m_i}} n_e S_p (1 + 0.414\eta) \sqrt{\frac{kT_i}{2e} + \frac{m_i V_i^2}{2e} - U_{cp} - U_{iz}^{**}}. \quad (8)$$

Eliminating  $(kT_i/2e + m_i V_i^2/2e - U_{cp})$  from (4) and (8) and substituting the expressions for the degree of ions dissociation (6) and electron density (7) into (4), we obtain the formula for extrapolating the ion current to the transition region

$$I_i^{extr}(U_{iz}) = -\sqrt{[I_p^{**}(U_{iz}^{**})]^2 + (S_s^{*-2} + D_\eta)} D_n (U_{iz}^{**} - U_{iz}).$$

The dependence of the relative error of the ion current extrapolation  $\bar{\epsilon}_{I_i} = (I_i^{extr} - I_i)/|I_i|$  on the normalized bias potential  $\bar{U}_{iz} = U_{iz}/|U_{fl}|$  for various

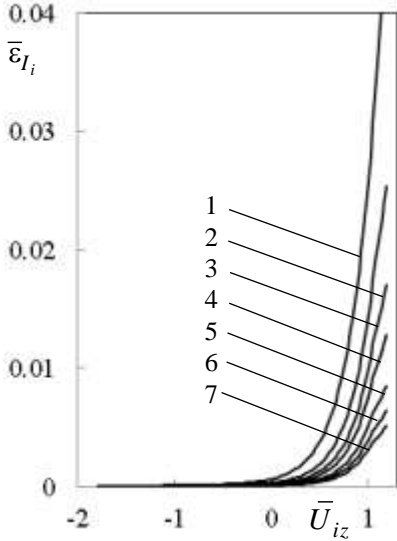


Fig. 3

area ratios  $S_s^{**}$  at  $U_{iz}^{**} = -30$  V is represented on Fig. 3. When calculating  $I_i^{extr}$  and  $I_i$  the exact values of the "measured" probe current  $I_p$  is simulated using the mathematical model of collecting current by the IPS [3]. The curves in the figure correspond to  $S_s^{**} = 100$  (1), 200 (2), 300 (3), 400 (4), 600 (5), 800 (6), 1000 (7).

An increase in the ratio of electrode areas leads to a decrease in the relative methodological error  $\bar{\epsilon}_{I_i}$  of the formula for extrapolating the ion current into the transition region of the CVC of IPS. The error does not exceed 2% at  $S_s^{**} = 200$  and it is 1% at  $S_s^{**} = 300$ .

Let's estimate the error of  $T_e$  determination as follows. Let A be the operator of the procedure for determining the electron temperature from the CVC of a cylindrical probe. Then within the model of a single cylindrical probe (short - "scp") the procedure writes as  $T_e = AI_p^{scp}$ , where  $I_p^{scp}$  is the "precise" probe current.

In the process of measuring probe current  $I_p^{scp}$  by the single cylindrical probe and  $I_p^{ips}$  by the IPS we obtain approximate values

$$\tilde{I}_p^{scp} = I_p^{scp} + \tilde{\delta}_I^{scp}, \quad \tilde{I}_p^{ips} = I_p^{ips} + \tilde{\delta}_I^{ips}, \quad (9)$$

where  $\tilde{\delta}_I^{scp}$ ,  $\tilde{\delta}_I^{ips}$  are random variables from the interval  $(-\delta_I, \delta_I)$ ,  $\delta_I > 0$  is the limiting absolute error of current measurement. Without breaking the generality, we assume that the errors in current measurement are equal for both measurement devices  $\tilde{\delta}_I^{scp} = \tilde{\delta}_I^{ips} = \tilde{\delta}_I$ .

Let  $\tilde{\varepsilon}_{T_e}^{scp}(\delta_I)$  and  $\tilde{\varepsilon}_{T_e}^{ips}(\delta_I)$  be the limiting relative errors of the procedure for determining the electron temperature  $T_e$  by measurements of probe currents (9) using a single cylindrical probe and IPS, respectively,  $\varepsilon_{T_e}^{ips}$  - the limiting relative methodological error of the  $T_e$  determining procedure by the IPS CVC. The above writes

$$\|\tilde{AI}_p^{scp} - T_e\|/T_e \leq \tilde{\varepsilon}_{T_e}^{scp}(\delta_I), \quad \|\tilde{AI}_p^{ips} - T_e\|/T_e \leq \tilde{\varepsilon}_{T_e}^{ips}(\delta_I), \quad \|AI_p^{ips} - T_e\|/T_e \leq \varepsilon_{T_e}^{ips}.$$

Performing elementary transformations of norms in a linear approximation:

$$\begin{aligned} \|\tilde{AI}_p^{ips} - T_e\| &= \|\tilde{AI}_p^{ips} - \tilde{AI}_p^{scp} + \tilde{AI}_p^{scp} - T_e\| \leq \|\tilde{AI}_p^{ips} - \tilde{AI}_p^{scp}\| + \|\tilde{AI}_p^{scp} - T_e\|, \\ \|\tilde{AI}_p^{ips} - \tilde{AI}_p^{scp}\| &= \|\tilde{AI}_p^{ips} + A\tilde{\delta}_I - \tilde{AI}_p^{scp} - A\tilde{\delta}_I\| = \|\tilde{AI}_p^{ips} - \tilde{AI}_p^{scp}\| = \|\tilde{AI}_p^{ips} - T_e\|, \end{aligned}$$

we obtain

$$\|\tilde{AI}_p^{ips} - T_e\| \leq \|\tilde{AI}_p^{ips} - \tilde{AI}_p^{scp}\| + \|\tilde{AI}_p^{scp} - T_e\|.$$

Dividing both parts of this inequality by  $T_e > 0$ , we get an expression for the limiting relative error of the  $T_e$  determination procedure based on the IPS CVC vs. the error of the procedure with single probe CVC:

$$\|\tilde{AI}_p^{ips} - T_e\|/T_e \leq \tilde{\varepsilon}_{T_e}^{ips}(\delta_I) = \varepsilon_{T_e}^{ips} + \tilde{\varepsilon}_{T_e}^{scp}(\delta_I). \quad (10)$$

The methodological error  $\varepsilon_{T_e}^{ips}$  of the procedure for determining the electron temperature for specific experimental conditions and methods for processing the measurement results (such as extrapolation of the ion current and numerical differentiation of  $\ln(I_e)$  with respect to the bias potential) can be estimated within the framework of a mathematical model of current collection by IPS.

Fig. 4 shows the dependences of the relative methodological error  $\varepsilon_{T_e}^{ips}$  on the normalized bias potential  $\bar{U}_{iz} = U_{iz}/|U_{fl}|$  for various area ratios  $S_s^{**}$  at  $U_{iz}^{**} = -30$  V. The curves stand to  $S_s^{**} = 400$  (1), 600 (2), 1000 (3), 3000 (4).

In the numerical calculations, the exact probe current  $I_p$  obtained from the mathematical model of current collection with IPS [3] serves as “measured” current. The symmetric difference quotient with argument step size  $dU$  is used in differentiating the function  $\ln[I_e(U_{iz})]$ . Results presented on Fig. 4 are obtained with  $dU = 0.1$  V.

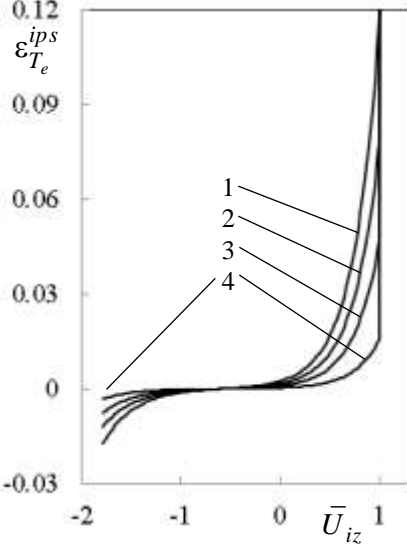


Fig. 4

As we may expect, as electrodes areas ratio  $S_s^{**}$  increases, the methodological error  $\varepsilon_{T_e}^{ips}$  decreases and doesn't exceed 5% in the transition region at  $S_s^{**} = 1000$ . Near the floating potential of the electrodes, where the bias potential equals zero, and at negative bias potentials  $U_{iz}^{**}$ , the error  $\varepsilon_{T_e}^{ips}$  is very small for all considered  $S_s^{**}$ . Presented in fig. 4 results serve as an upper estimate of the methodological error  $\varepsilon_{T_e}^{ips}$  for the

procedure for determining the electron temperature.

Within the framework of the accepted model of the IPS current collection, it follows from relation (2) that in the transition region, where the equilibrium potential is close to the floating potential of the reference electrode, the function  $f(U_{iz}) = \ln[I_e(U_{iz})]$  is almost linear. To differentiate the function, we use its approximation by a polynomial of the 1st degree using the least squares method on the interval  $U_{iz} \in (U_*, U_{**})$  within the transition region of the CVC ( $U_{fl} \leq U_* \leq 0 < U_{**} \leq |U_{fl}|$ ). Fig. 5 shows the dependence of the relative methodological error  $\varepsilon_{T_e}^{ips}$  of the procedure for determining the electron temperature at  $U_* = U_{fl}$  (a) and  $U_* = 0.1U_{fl}$  (b) on the right boundary of the potential interval  $\bar{U}_{**} = U_{**}/|U_{fl}|$  for various area ratios  $S_s^{**}$  at  $U_{iz}^{**} = -30$  V. The probe current  $I_p^{ips}$  is set on the interval  $[U_*, U_{**}]$  with the step of 0.5 V. The curves in the Fig. 5 correspond to  $S_s^{**} = 100$  (1), 300 (2), 500 (3), 700 (4), 1000 (5), 3000 (6).

The presented results show that, compared with local differentiation using the symmetric difference quotient (Fig. 4), numerical differentiation using approximation of the logarithm of the electron current on the interval leads to a significantly smaller methodological error in the procedure of determining the electron temperature. As the electrodes surface areas ratio  $S_s^{**}$  increases, the methodological error

$\varepsilon_{T_e}^{ips}$  decreases and does not exceed 3% when using the interval  $(U_{fl}, -U_{fl})$  at  $S_s^{**} \geq 100$  (Fig. 5, a)) and the interval  $(0.1 \cdot U_{fl}, -U_{fl})$  at  $S_s^{**} \geq 300$  (Fig. 5, b)) in the procedure for determining the electron temperature.

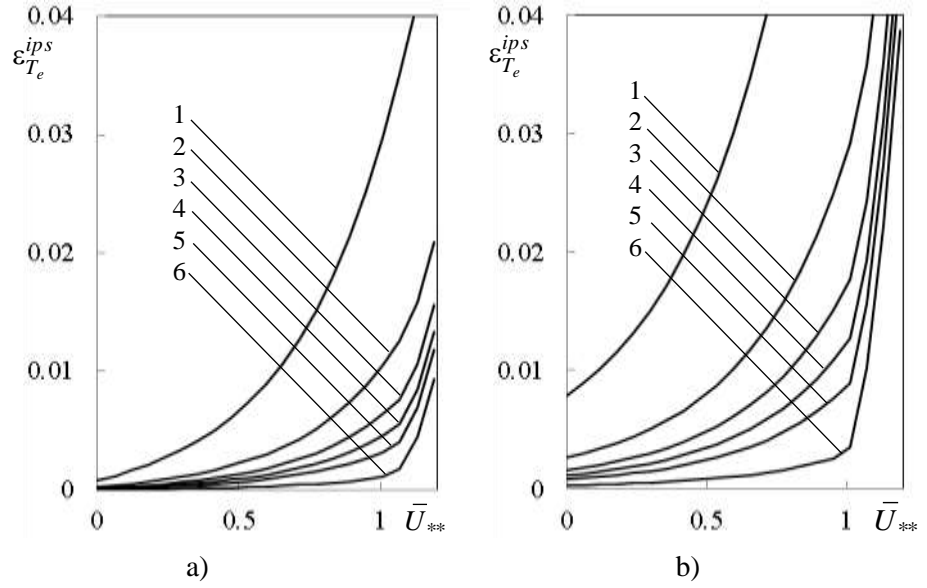


Fig. 5

Estimated relative methodological error  $\varepsilon_{T_e}^{ips}$  of the proposed procedure of  $T_e$  determination by IPS (Fig. 5) appears to be significantly smaller than the error  $\tilde{\varepsilon}_{T_e}^{scp}$  of the classical procedure of  $T_e$  determination by the VAC of a single cylindrical probe [4].

The obtained estimation of the relative methodological error  $\varepsilon_{T_e}^{ips}$  helps to choose the proper value of the parameter  $S_s^{**}$  and interval of bias potential on the IPS CVC for adequate determination of the electron temperature. So, for example, from Fig. 5, b) we derive that to hold an error  $\varepsilon_{T_e}^{ips}$  less than 1%, at  $S_s^{**} = 300$  we use interval  $U_{iz} \in (0.1U_{fl}, 0.6|U_{fl}|)$  for numerical differentiation, and interval  $U_{iz} \in (0.1U_{fl}, 0.8|U_{fl}|)$  at  $S_s^{**} = 500$ .

Numerical modeling of temperature  $T_e$  determination from the results of probe currents measurement (9) is carried out. The obtained results confirmed the estimate (10). The simulation results and the estimates obtained in [3] show that it is rational to measure the probe currents  $I_p^{**}(U_{iz}^{**})$  in the ion region and  $I_p(U_{iz})$  in the transition region of the CVC at the largest possible ratio of electrodes surface areas  $S_s^{**}$ . It is advisable to measure probe currents  $I_p^*(U_{iz})$  in the electron region of the CVC at  $S_s^* = 200-400$ .

**Conclusions.** On the basis of the classical procedure for determining the electron temperature by the CVC of a single cylindrical probe, a procedure is developed that makes use of CVC of isolated probe system in a supersonic jet of a collisionless plasma of diatomic gas.

An approximation of the floating potential of an isolated probe system in a strongly nonequilibrium plasma of the gas discharge source jet is obtained, which makes it possible to determine the boundaries of the transition region of the CVC using the a priori information about plasma parameters. A calculation formula is obtained for extrapolating the functional dependence of the ion probe current on the bias potential in the transition region of the CVC.

The possibility of determining the electron temperature from the CVC of an IPS with cylindrical electrodes using the classical procedure with a single cylindrical probe is substantiated. It is shown that the error in determining the electron temperature by the currents measured with the IPS is the sum of the methodological error of the procedure and the measurement error which is also present in measurement of the single cylindrical probe current. Based on the results of a numerical study, quantitative characteristics of the influence of electrodes surface areas ratio on the methodological error in determining the temperature of plasma electrons in laboratory modeling of flow conditions in the ionosphere are obtained.

Numerical modeling of errors in measurement of probe currents showed that, within the accepted assumptions, the accuracy of determining the electron temperature when using an isolated probe system is comparable to the accuracy of measurements with a single cylindrical probe.

1. Shuvalov V.A., Pis'menniy N.I., Lazuchenkov D.N., Kochubey G.S. Probe diagnostics of laboratory and ionospheric rarefied plasma flows. *Instruments and Experimental Techniques*. 2013. V. 56. No. 4. P. 459–467. <https://doi.org/10.1134/S002044121304009X>
2. Lazuchenkov D. N., Lazuchenkov N. M. Determination of parameters of a dissociated supersonic rarefied plasma flow by current-voltage characteristics of isolated system of cylindrical probes. *Tech. Mech.* 2020. No. 2. Pp. 80 – 88. <https://doi.org/10.15407/itm2020.02.080>
3. Lazuchenkov D. N. Determination of plasma parameters in a jet of a gas-discharge source using an isolated probe system with cylindrical electrodes. *Tech. Mech.* 2022. No. 4. Pp. 121–130. <https://doi.org/10.15407/itm2022.04.121>
4. Chung, P. M., Talbot L., Touryan K. J. *Electric Probes in Stationary and Flowing Plasmas*. Springer-Verlag, 1975. 150 p. <https://doi.org/10.1007/978-3-642-65886-0>
5. Kozlov O. V. *Electric probe in plasma*. Atomizdat, 1969. 291 p.
6. Godard R., Laframboise J.G. Total current to cylindrical collectors in collisionless plasma flow. *Planetary and Space Sciences*. 1983. V. 31. No. 3. Pp. 275–283. [https://doi.org/10.1016/0032-0633\(83\)90077-6](https://doi.org/10.1016/0032-0633(83)90077-6)

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