

MODELING OF ELECTRON TEMPERATURE DETERMINATION USING A STATIONARY CYLINDRICAL LANGMUIR PROBE UNDER IONOSPHERIC CONDITIONS

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Метою роботи є теоретичне обґрунтування застосування класичних співвідношень теорії одиночного циліндричного зонда для визначення температури електронів за вольтамперною характеристикою плаваючої зондової системи "зонд – плазма – корпус надмалого супутника" в умовах іоносфери. Зондові вимірювання розглянуті на прикладі циліндричної геометрії зонда та опорного електрода (корпусу супутника) при надзвуковому поперечному вільномолекулярному обтіканні. Іоносферна плазма вважається максвелівською, складається з електронів та однозарядних атомарних іонів кисню та водню. Моделювання проведено на основі розробленої раніше математичної моделі, що визначає електричну та газодинамічну взаємодію в плаваючій системі "зонд – плазма – корпус супутника" через параметри плазми, зондової системи та потенціал зсуву зонда щодо корпусу супутника.

Виконано моделювання визначення температури електронів за класичною процедурою теорії одиночного циліндричного зонда при вимірюваннях зондових струмів на початковій ділянці іонної області та в перехідній області вольтамперної характеристики плаваючої зондової системи. В рамках використаної моделі отримано кількісні оцінки методичної похибки визначення температури електронів в умовах невизначеності параметрів іоносферної плазми – іонного складу, ступеня нерівноважності, швидкості обтікання. Показано, що при відношенні площ корпусу супутника і зонда понад 300 методична похибка не перевищує 2 %. Отримано числові та аналітичні оцінки похибки визначення температури електронів за розрахунковими формулами теорії одиночного зонда залежно від точності вимірювання зондових струмів та потенціалів. Показано, що в рамках прийнятої моделі збирання струмів методична похибка використання розрахункових формул одиночного зонда істотно менша за похибку розрахункових формул при точності вимірювання струмів і потенціалів в 1 %.

Отримані результати можуть бути використані для підготовки та проведення діагностики іоносферної плазми з використанням надмалих супутників.

Ключові слова: іоносферна плазма, іони атомарного кисню та водню, надмалі космічні апарати, плаваюча зондова система, одиночний циліндричний зонд, достовірність визначення температури електронів.

The goal of this article is to theoretically substantiate the applicability of classical formulas in the theory of a single cylindrical probe to determining the electron temperature using the current-voltage characteristic of a floating probe system of probe – plasma – ultrasmall spacecraft structure in ionospheric conditions. Probe measurements are considered using a cylindrical probe and a cylindrical reference electrode (spacecraft structure) in a supersonic transverse free-molecular flow. The ionospheric plasma is considered to be Maxwellian and consist of electrons and singly charged atomic ions of oxygen and hydrogen. The modeling is based on a mathematical model developed earlier, which determines electrical and gas-dynamic interaction in the floating system of probe – plasma – satellite structure as a function of the plasma and probe system parameters and the bias potential of the probe relative to the spacecraft structure.

Electron temperature determination was simulated using the classical procedure of the theory of a single cylindrical probe based on measuring the probe currents in the low voltage part of the ion region and the transition region of the current-voltage characteristic of a floating probe system. For the model used, the methodological error in determining the electron temperature was quantitatively estimated taking into account the uncertainty in ionospheric plasma parameters, such as the ion composition, degree of nonisothermality, and flow velocity. It was shown that, for a satellite-to-probe area ratio greater than 300, the methodological error does not exceed 2%. Numerical and analytical estimates of the error in determining the electron temperature using the calculation formulas of the single-probe theory were obtained as a function of the probe current and potential measurement accuracy. It was shown that, within the adopted current collection model, the methodological error of using the calculation formulas for a single probe is significantly less than the error of the calculation formulas at a current and potential measurement accuracy of 1%.

The obtained results may be used in preparing and conducting ionospheric plasma diagnostics using ultrasmall spacecraft.

Keywords: ionospheric plasma, atomic oxygen and hydrogen ions, ultrasmall spacecraft, floating probe system, single cylindrical probe, reliability of electron temperature determination.

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ISSN 1561-9184 (Print) ISSN 2616-6380 (Online)

Технічна механіка. 2026. № 3.

Introduction. Among contact methods for ionospheric plasma diagnostics, the most widely used is the stationary cylindrical Langmuir probe [1–6]. This is primarily due to the simplicity of the measuring equipment design, a well-developed theory, and acceptable accuracy in measuring the electron density and temperature in the vicinity of a satellite.

The reference electrode of a Langmuir probe is typically the surface of conducting elements of the satellite body that have electrical contact with the plasma. Since the probe measurement system onboard the satellite is floating, the reference electrode acquires such electrical potential at which the total current to the satellite equals zero [7]. The rather stringent condition $S_s = S_{cp}/S_p > 10^3$ for the ratio of the areas of the reference electrode S_{cp} and the probe S_p and highly rarefied ionospheric plasma significantly limit the registered probe currents when using the single Langmuir probe measurement scheme on micro- and nanosatellites.

This article is a continuation of the work [8] on the substantiation of the applicability of the classical relations of the theory of a single cylindrical Langmuir probe for the diagnostics of ionospheric plasma onboard small satellites. In the work [8], the effect of the geometric parameter S_s and the error in measuring currents on the reliability of determining the electron density using the classical relations of the theory of a single cylindrical probe in the low voltage part of the electron region of the current-voltage characteristic (CVC) of the floating probe system (FPS) is estimated. In this article, the effect of the geometric parameter on the reliability of determining the electron temperature of the ionospheric plasma at altitudes from 400 km to 800 km, where the majority of ions are hydrogen and oxygen [9], is quantitatively estimated.

Problem formulation and mathematical model for probe measurements onboard a very small satellite under ionospheric conditions are presented in [8]. It is assumed that the FPS consists of sufficiently long cylindrical electrodes – a probe with a base radius r_p and a reference electrode (satellite body) with a base radius r_{cp} . The electrodes are placed transversely in a supersonic ionospheric plasma flow with a mass velocity V . The end surfaces of the electrodes are insulated from the plasma.

The charged particles of the ionospheric plasma are electrons and singly charged oxygen O^+ and hydrogen H^+ ions. The unperturbed plasma is considered to be Maxwellian, quasi-neutral, and nonisothermal. The ion temperatures are identical, $T_{H^+} = T_{O^+} = T_i$, and the degree of nonisothermality is characterized by the parameter $\beta = T_e/T_i$, where T_e is the electron temperature. The ion composition of the plasma is characterized by the parameter $\chi_n = n_{H^+}/(n_{H^+} + n_{O^+}) \equiv n_{H^+}/n_e$, where n_{H^+} , n_{O^+} are the densities of ions H^+ and O^+ , respectively, n_e is the electron density.

We consider that the electrostatic and gas-dynamic influence of the electrodes on each other is weak; the side surfaces completely absorb the charge of incident particles, and there is no emission current from the surfaces; the flow around the electrodes is free-molecular; the effect of magnetic field on the probe current is insignificant; the presence of different species of ions in the plasma does not significantly alter the self-consistent electric field near the electrodes.

The main geometric parameter of a FPS is the ratio of the current-collecting surfaces of the reference electrode and the probe, $S_s = S_{cp}/S_p$. The case $S_s \rightarrow \infty$ corresponds to the single-probe theory. It is necessary to evaluate the applicability of the formulas of the single-cylindrical probe theory to determining the electron temperature T_e from FPS probe current measurements in the ion and transition regions of the CVC.

Mathematical model of current collection. The electrical and gas-dynamic interaction of a cylinder with a plasma flow is determined by the ion velocity ratio $S_i = V/u_i$, the characteristic cylinder size relative to the Debye length $\xi = r_c/\lambda_d$, the electric potential of the cylinder relative to the undisturbed plasma U_p , and the ratio of the temperatures of the charged particles $\beta = T_e/T_i$. Here, u_i is the thermal velocity of ions of species i with mass m_i , r_c is the cylinder base radius, and λ_d is the Debye length.

A mathematical model for currents collection by cylindrical electrodes in supersonic flow of ionospheric plasma is substantiated in [8]. That model takes into account different values of parameter ξ for the probe and reference electrode and different velocity ratios S_i for oxygen and hydrogen ions in the flow, S_i is 4 times smaller for hydrogen ions than that for oxygen ions. An approximation of the dependence of the ion current collected by the cylinder on the parameters ξ , S_i , and the cylinder's potential ϕ relative to the plasma is developed using the classical Langmuir asymptotic relations [10] and the calculation results from [11–13] of solving a system of two-dimensional Vlasov–Poisson equations for transverse free-molecular flow around a cylinder. In dimensionless quantities, the total current to the cylinder is estimated by the relation (the electron current to the cylinder is positive):

$$\bar{I}_c(\phi) = \bar{I}_e(\phi) - \bar{I}_i(\phi), \quad \bar{I}_i(\phi) = \sqrt{\mu_2/\beta} \left(4\chi_n \cdot \bar{I}_{H^+}(\phi) + (1 - \chi_n) \cdot \bar{I}_{O^+}(\phi) \right), \quad (1)$$

where $\bar{I}_c$, $\bar{I}_e$, $\bar{I}_i$ stand for the total, electron, and ion currents to the cylinder, respectively, normalized to the thermal electron current; $\bar{I}_{O^+}$, $\bar{I}_{H^+}$ are the currents to the cylinder of ions O^+ , H^+ , normalized to the thermal currents of ions of the corresponding species, $\phi = eU/kT_e$ is the dimensionless electric potential (U is the dimensional potential, k is the Boltzmann constant, e is the unit charge), $\mu_2 = m_e/m_{O^+}$ is the ratio of the masses of charged particles. Calculation formulas for the currents $\bar{I}_e$, $\bar{I}_{O^+}$ and $\bar{I}_{H^+}$ are given in [8].

In the ionosphere, the FPS is always at an equilibrium potential, defined by the zero total current of charged particles through all collecting surfaces of the electrodes. The potential of the satellite body (reference electrode) U_{cp} relative to the undisturbed plasma is almost always negative. The probe potential relative to the undisturbed plasma writes $U_p = U_{iz} + U_{cp}$, where U_{iz} is the bias potential which is probe potential relative to the reference electrode potential. A probe measurement is registering the current I_p in the “probe–plasma–reference electrode” circuit while modulating the bias potential U_{iz} .

The dimensionless probe current $\bar{I}_p$ at the bias potential φ_{iz} is determined by solving a system of nonlinear equations:

$$\bar{I}_p(\varphi_{iz}) = \bar{I}_c(\varphi_{iz} + \varphi_{cp}), \quad (2)$$

$$S_s \bar{I}_c(\varphi_{cp}) + \bar{I}_c(\varphi_{iz} + \varphi_{cp}) = 0, \quad (3)$$

where φ_{cp} is the equilibrium potential of the reference electrode relative to the undisturbed plasma potential, corresponding to the bias potential φ_{iz} . Here and below, the index "cp" refers to the reference electrode, and the index "p" refers to the probe.

We assume that the following constraints hold for the probe and reference electrode:

$$\xi_p = r_p / \lambda_d < 1, \quad \xi_{cp} = r_{cp} / \lambda_d \leq 10.$$

Thus, relations (2), (3), (1) define the electrical and gas-dynamic interaction (the dimensionless CVC $\bar{I}_p(\varphi_{iz})$) in the floating system "probe-plasma-reference electrode" through the dimensionless parameters $\chi_n, \mu_2, \beta, S_i, S_s$ and the bias potential φ_{iz} .

The dimensionless parameters $\chi_n, \beta, S_i, S_s, \varphi_{iz}$ are determined through the unperturbed plasma parameters $n_{H^+}, n_{O^+}, n_e, T_e, T_i, V$, the geometric parameters of the probe system S_p, S_{cp} , and the probe bias potential U_{iz} . The dimensional CVC of the FPS is determined by the relation $I_p(U_{iz}) = j_e \cdot S_p \cdot \bar{I}_p(\varphi_{iz})$, where $j_e = e \sqrt{k/2\pi m_e} n_e \sqrt{T_e}$ is the density of the thermal electron current.

Direct problem of probe measurements is to calculate the CVC of the probe $I_p(U_{iz})$ for the given values of the unperturbed plasma parameters (n_e, χ_n, T_e, T_i, V) and parameters of the FPS (S_p, S_{cp}). Similarly to the case of a single cylindrical probe (characterized by $S_s \rightarrow \infty$), the CVC of the FPS can be conventionally separated into three characteristic regions: the ion saturation region ($U_{iz} < U_{iz}^*, I_e \ll I_i$), the electron saturation region ($U_{iz} > U_{iz}^{**}, I_e \gg I_i$), and the transition region ($U_{iz}^* < U_{iz} < U_{iz}^{**}$), where U_{iz}^*, U_{iz}^{**} are the accepted low and high boundaries of the transition region of the CVC, respectively.

It is familiar that the CVC of a FPS differs most significantly from that of a single cylindrical probe in the electron saturation region. The ion region of the CVC for the FPS with the electrodes areas ratio $S_s > 20$ is practically equal to that of a single probe, for which the potential of the reference electrode relative to the plasma is constant. Fig. 1 shows in dimensionless form the dependences of electron to ion currents ratio on the bias potential φ_{iz} in the transition region of the CVC at $S_s = 600$ for $\chi_n = 0$ (thick solid curve), $\chi_n = 0.3$ (thin solid curve), and $\chi_n = 0.7$ (dotted curve). The calculations are performed for $S_i = 5, \mu_2 = 3.4 \cdot 10^{-5}$ and $\beta = 1.3$.

The upper boundary U_{iz}^{**} of the transition region corresponds to the zero probe potential U_p relative to the plasma. In dimensionless form, the upper boundary of the transition region is determined by the condition

$$\phi_{iz} = -\phi_{cp} . \quad (4)$$

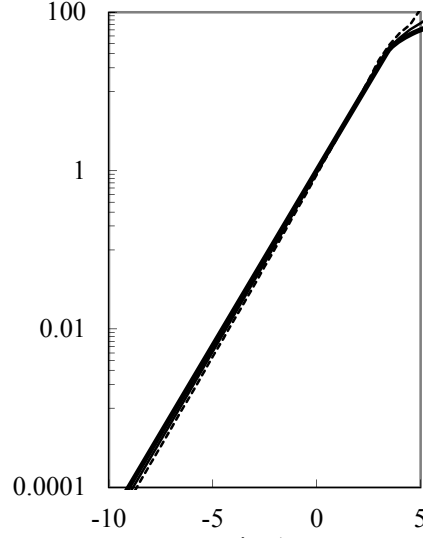


Fig. 1

Thus, within the framework of the adopted current collection model by FPS, ϕ_{iz}^{**} is determined quite accurately by solving the system of nonlinear equations (3), (4). Fig. 2 represents the dependence of ϕ_{iz}^{**} on the electrode areas ratio S_s for $\chi_n = 0$ (thick solid curve), 0.1 (thick dashed curve), 0.3 (thin solid curve), 0.5 (thin dashed curve), and 0.7 (thin dotted curve).

Fig. 3 shows the dependence of the dimensionless equilibrium potential ϕ_{cp} of the reference electrode on the bias potential ϕ_{iz} near the transition region of the CVC for $\chi_n = 0.5$ at $S_s = 200$ (dotted curve), 300 (thin dashed curve), 400 (thin solid curve), 800 (thick solid curve), and 1600 (thick dashed curve).

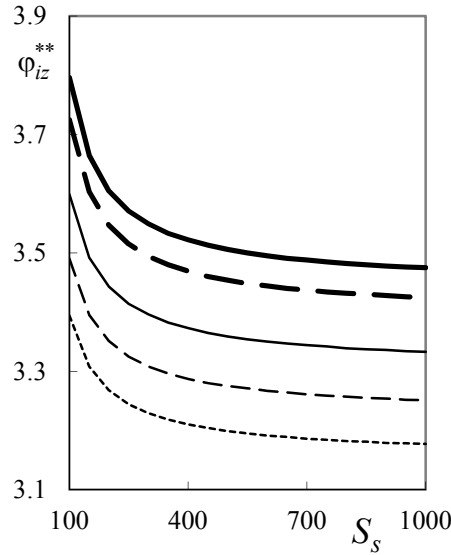


Fig. 2

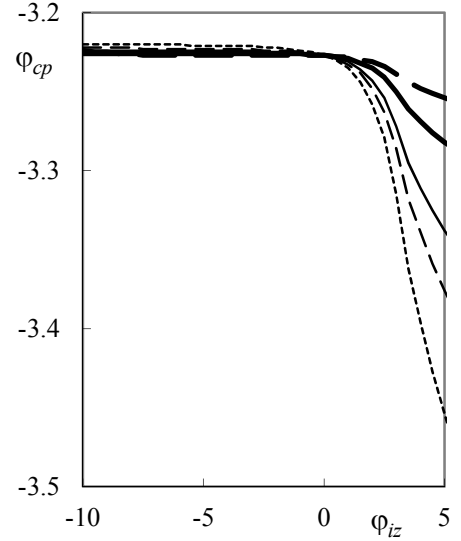


Fig. 3

We notice that changing in the parameters S_s and χ_n within the considered limits leads to a fairly significant change in the equilibrium potential ϕ_{cp} and the upper boundary of the transition region ϕ_{iz}^{**} . Since, in general, the electron temperature can be determined under the uncertainty in the ion composition and the

electrodes areas ratio, for modeling we use the lowest value of $\varphi_{iz}^{**} = 3.2$ (see Fig. 2), thereby reducing the transition region of the CVC.

The data presented in Fig. 1 at negative bias potentials show that the lower boundary of the transition region φ_{iz}^* is quite arbitrary, and we determine it by the ratio of the electron current to the ion current at the probe $d = |I_e/I_i| = |(I_p - I_i)/I_i|$. Essentially, d is the relative deviation of the probe current from ion current in the ion region of the CVC. An increase in the parameter χ_n from 0 to 0.7 for $\varphi_{iz} < 0$ is decreasing d by 10% to 30%, so for given d^* , φ_{iz}^* is shifting toward zero reducing the transition region. Therefore, due to the uncertainty of the plasma ion composition χ_n , during modeling we use the dependence of d on φ_{iz} at $\chi_n = 0$, which is approximated $\varphi_{iz}^* = 0.0022 + 2.26 \cdot \lg(d^*)$. We select such d^* at which electron current is smaller than measuring current error ε_I , so $d^* \leq \varepsilon_I$.

Inverse Problem of Probe Measurements. Let's model the measurements in Ionosphere using FPS utilizing the mathematical model of current collection (1) – (3). We consider the problem of determining the electron temperature (parameter T_e of the mathematical model) based on the probe current measurements $I_p(U_{iz})$ by the FPS in the transition and high voltage side of the ion regions of the CVC. We use a procedure for determining the electron temperature from the CVC of a single stationary cylindrical probe in a plasma flow with single-species ions [14].

The classical procedure for determining the electron temperature includes two main stages of processing the CVC of a single cylindrical probe: extrapolation of the ion current $I_i^{extr}(U_{iz})$ from the ion saturation region to the transition region of the CVC and differentiation of the experimentally obtained linear function $\ln[I_e(U_{iz})]$ in the transition region of the CVC.

Within the framework of the mathematical model of current collection (1) – (3), (1), the methodological error of applying the procedure for determining T_e using a single cylindrical probe is estimated by calculating $\bar{T}_e$ using the classical approach from the currents $I_p(U_{iz})$ obtained from the solution of problem (2), (3), (1), and then comparing it with T_e . The relative error $\varepsilon_{Te} = (\bar{T}_e - T_e)/T_e$ corresponds to the specific measurement conditions (bias potential U_{iz} at measuring probe currents $I_p(U_{iz})$) and the method of processing the results (methods of ion current extrapolation and numerical differentiation of $\ln[I_e(U_{iz})]$).

In the modeling, the dimensional upper boundary of the transition region is specified as $U_{iz}^{**} \approx 3.2 kT_e/e$, and the lower boundary as $U_{iz}^* \approx -4 kT_e/e$.

Extrapolation of the ion current from the ion region to the transition region of the CVC is based on the classical Langmuir asymptotic formula, which specifies the current to the thin cylinder in the ion-attracting electric field to be $\sqrt{-\varphi_c}$ [10]. For plasma with single-species ions, due to the linearity of $I_i^2(U_{iz}) \approx I_p^2(U_{iz})$ in the ion region of the CVC, the following relation holds:

$$I_i(U_{iz}) \approx -\sqrt{I_p^2(U_{iz1}) \frac{U_{iz} - U_{iz2}}{U_{iz1} - U_{iz2}} - I_p^2(U_{iz2}) \frac{U_{iz} - U_{iz1}}{U_{iz1} - U_{iz2}}}, \quad (5)$$

where $U_{iz2} < U_{iz1} \leq U_{iz}^*$.

Let I_i^{extr} be the ion current calculated by (5) for bias potentials U_{iz} from the transition region of the CVC ($U_{iz}^* < U_{iz} \leq U_{iz}^{**}$). Fig. 4 shows the dependence of the relative extrapolation error of the ion current $\varepsilon_{I_i} = (I_i^{extr} - I_i)/I_i$ (thin curves) and

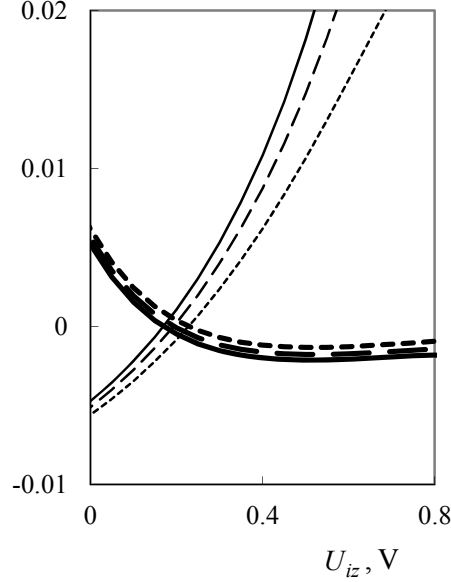


Fig. 4

electron current $\varepsilon_{I_e} = (I_p - I_i^{extr} - I_e)/I_e$ (thick curves) on the bias potential U_{iz} (in volts) for $\chi_n = 0.5$ at $S_s = 100$ (dotted curve), 200 (dashed curve), and 1000 (solid curve). The calculations were performed for $U_{iz1} = -1$ V, $U_{iz2} = -4$ V.

The presented results illustrate the familiar fact of suppression of the ion current by the electron current in the transition region of the CVC. As the bias potential increases higher from the ion region, a significant increase in the ion current extrapolation error ε_{I_i} occurs, but the relative error in determining the electron current ε_{I_e} decreases and does not exceed fractions of a percent.

Electron temperature is determined using the calculation formula for a single probe:

$$T_e \approx \frac{e}{k} \left[\frac{d \ln(I_p - I_i^{extr})}{dU_{iz}} \right]^{-1}. \quad (6)$$

Within the framework of the theory of a single cylindrical probe, this formula is exact, since the potential of the reference electrode is constant. In the general case of a FPS, as shown above, the potential U_{cp} in the transition region changes quite noticeably. Fig. 5 represents the effect of parameters χ_n (a), T_e (b), V (c) on the methodological error $\bar{\varepsilon}_{T_e}$ at $S_s = 200$ (dotted curves), 300 (thin dashed curves), 400 (thin solid curves), 800 (thick solid curves), 1600 (thick dashed curves) and an upper estimate of the effect of these parameters under ionospheric conditions depending on S_s (d). During the modeling, the differentiation of the logarithm of the function $I_e \approx I_p - I_i^{extr}$ is carried out using linear approximation by the least squares method.

An analysis of the modeling results shows that variations in the flow velocity V and parameter β do not significantly affect the error in determining the electron temperature. A change in the plasma ion composition (parameter χ_n) results in a

change in $\bar{\varepsilon}_{T_e}$ up to 0.5 %. The greatest effect is exerted by the electron temperature T_e and the electrode areas ratio S_s . A decrease in these parameters leads to an increase in the methodological error. For $S_s > 100$, the error $\bar{\varepsilon}_{T_e}$ does not exceed 5 %, and for $S_s > 300$, it does not exceed 2 %. Note that with a further increase in electrodes areas ratio S_s , the methodological error $\bar{\varepsilon}_{T_e}$ decreases, but does not approach zero, it is about 1 % for $S_s = 2000$.

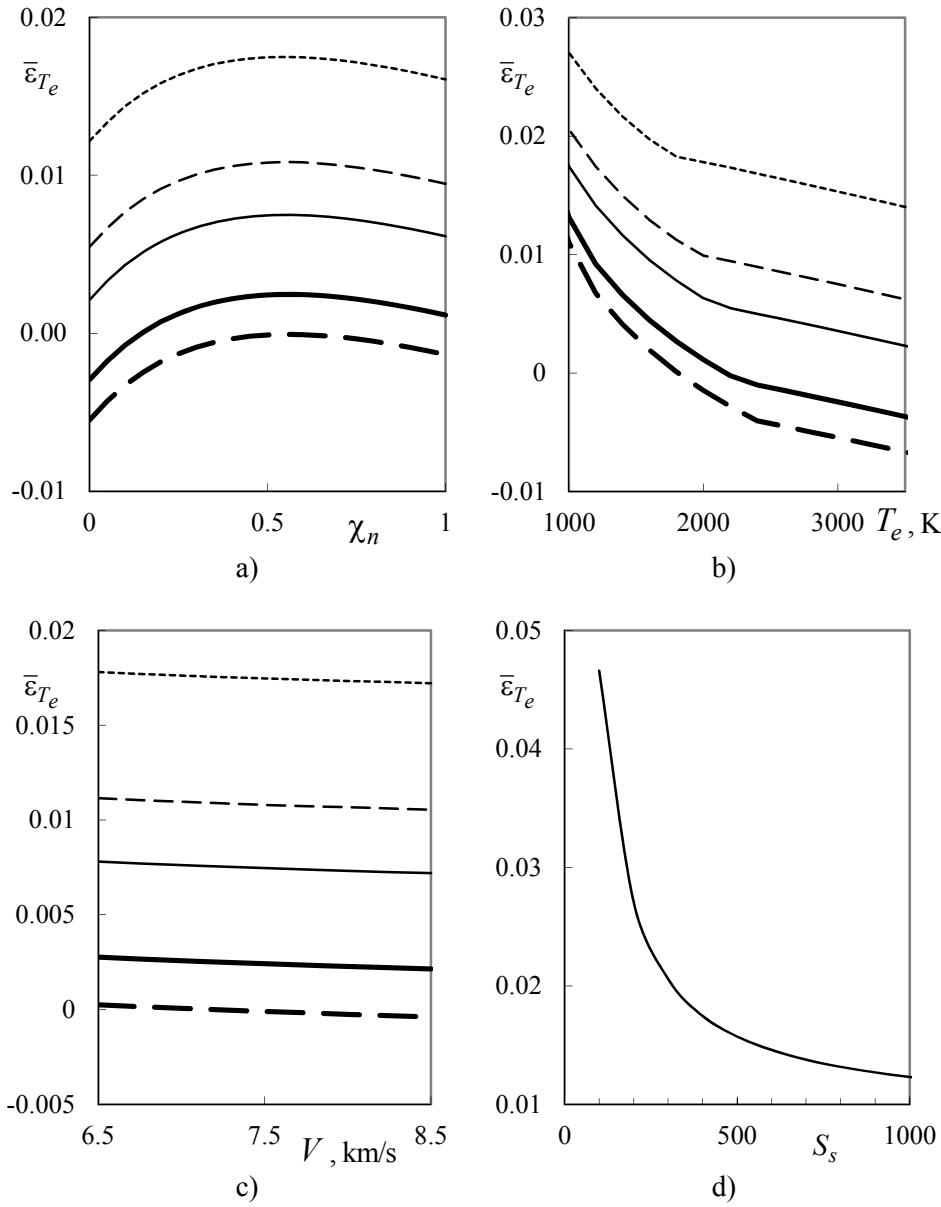


Fig. 5

The results presented in Fig. 5, d) are, within the framework of the current collection model (2), (3), (1), an upper estimate of the methodological error $\bar{\varepsilon}_{T_e}$ with uncertainty in the model parameters χ_n , V , β , T_e for the procedure for determin-

ing the electron temperature in ionospheric conditions using calculations based on the single-probe theory. The results show that the level of methodological error of the procedure for the T_e determination using FPS is significantly less than the level of actual error in determining the electron temperature by the CVC of a single cylindrical probe [14].

Probe measurements errors. To determine the electron temperature from the CVC of the FPS, formulas (5) and (6) are used. These formulas are accurate within the framework of the theory of a single probe in a plasma flow with single-species ions [14]. To estimate the effect of bias potential and probe currents measurements errors on the error in determining the electron temperature by (5), (6), we use a two-point difference approximation during numerical differentiation in formula (6):

$$T_e \approx \frac{e}{k} \frac{U_{iz4} - U_{iz3}}{\ln[I_p(U_{iz4}) - I_i^{extr}(U_{iz4})] - \ln[I_p(U_{iz3}) - I_i^{extr}(U_{iz3})]}, \quad (7)$$

where $U_{iz}^* < U_{iz3} < U_{iz4} \leq U_{iz}^{**}$.

For temperatures T_e and $\tilde{T}_e$, calculated using (5) and (7), respectively, for "actual" $I_p(U_{iz})$ and "measured" $\tilde{I}_p(\tilde{U}_{iz})$ probe currents, the following estimate holds

$$\left| \frac{\tilde{T}_e - T_e}{T_e} \right| \leq \varepsilon_{T_e} \approx 3\varepsilon_{I_{tr}} + 4\varepsilon_{I_{ir}} + 4\varepsilon_U. \quad (8)$$

Here ε_{T_e} is the maximum relative error in determining the electron temperature using formulas (5), (7); $\varepsilon_{I_{tr}}$, $\varepsilon_{I_{ir}}$, ε_U are the maximum relative errors in measuring probe currents in the transition region ($|\tilde{I}_p - I_p|/I_p \leq \varepsilon_{I_{tr}}$), in the ion region ($|\tilde{I}_p - I_p|/I_p \leq \varepsilon_{I_{ir}}$), and bias potentials ($|\tilde{U}_{iz} - U_{iz}|/U_{iz} \leq \varepsilon_U$), respectively. The separation between the measurement conditions for the ion and transition regions of the CVC is due to the significant difference (by an order of magnitude) in the levels of the measured currents. Estimate (8) is obtained for ionospheric conditions at $|U_{iz3}| \ll U_{iz4}$, taking into account the modeling results, which show that in the ion saturation region, the ratio of probe currents $\tilde{I}_p(U_{iz1})/\tilde{I}_p(U_{iz2})$ is the largest when $\chi_n = 0$.

As one can see, the relative measurements error ε_{T_e} doesn't depend explicitly on the geometric parameter S_s . However, the total error, including the methodological error $\bar{\varepsilon}_{T_e}$ of the procedure for determining T_e , depends on the electrodes areas ratio S_s , as shown at Fig. 5, d).

The estimates and modeling results show that, with a current and potential measurement accuracy of 1 %, the methodological error $\bar{\varepsilon}_{T_e}$ of using the calculation formulas of the single-probe theory to determine the electron temperature is significantly less than the error ε_{T_e} of calculations using formulas (5) and (7).

Conclusions. The applicability of classical single-cylindrical probe theory to determine the electron temperature from floating probe system current measurements in ionospheric conditions is theoretically substantiated. The substantiation is based on a mathematical model that describes the electrical and gas-dynamic inter-

actions in the floating system “probe–plasma–spacecraft body” through the parameters of the plasma, probe system, and probe bias potential.

Determining electron temperature is modeled using the classical procedure of single-cylindrical probe theory by measuring probe currents in the ion saturation region and transition region of the CVC of the floating probe system. Methodological error in determining electron temperature under conditions of uncertainty in ionospheric plasma parameters (ion composition, degree of nonisothermality, and flow velocity) is quantitatively estimated within the framework of the FPS model. It is shown that, for the spacecraft body to probe area ratio greater than 300, the methodological error does not exceed 2 %.

The obtained numerical and analytical estimates make it possible to select the parameters and measurement modes of the floating probe system and to determine the required measurement accuracy when planning and conducting ionospheric plasma diagnostics experiments onboard ultra-small spacecraft.

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Received on July 28, 2026;
approved on September 18, 2026;
published on September 28, 2026.