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# COOLED CYLINDRICAL LANGMUIR PROBE IN A SLOWLY MOVING PLASMA

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Probe measurements in the plasma of laboratory flames are carried out with flow around the probe at low Reynolds number (Re ~ 1). The complexity of theoretical determination of the volt–ampere characteristics for a probe in a moving high density plasma leads to the situation that currently they are limited to calculating saturation currents [1] which is much simpler. The saturation current at a cylindrical probe with Re ≤ 15 has been calculated in [2]. Determination of volt–ampere characteristics for Re << 1 is simplified when it is possible to use methods of asymptotic analysis. Cylindrical probe characteristics for these conditions with moderate potentials have been obtained in [3].

As in many other works, it was assumed in [2, 3] that probe temperature equals that of the stream which is constant within the flow field. In fact the probe temperature is always markedly lower. It is limited from above by the temperature for the start thermoelectron emission which distorts the results of determining the ion current. Quite a low probe temperature is normally achieved in experiments without special cooling and the fact that the probe is introduced into the plasma for a short time. However, in theory a probe whose surface temperature is below the stream temperature is called cooled.

For a cooled probe in a flow field there is a marked change in ion and electron diffusion coefficients and also the density of neutral gas. The effect of these factors on spherical probe characteristics in an immobile plasma was studied in [4], and on the saturation current for spherical and cylindrical probes in a plasma moving at high Re it was studied in [5]. The effect of the temperature factor on the saturation current of a spherical probe in a slowly moving plasma with Re << 1 was determined in [6]. The result of these studies is a weak dependence of saturation current on probe temperature.

In the present work, which is a development of [3], studies are continued for a cylindrical probe in a moving plasma with Re << 1.

1. We consider flow of a dense plasma around a cylindrical conducting body (probe) of infinite length whose axis of symmetry is arranged perpendicular to the velocity of the approach stream. Flow past occurs with Re << 1. The plasma consists of neutral particles, positively singly-charged ions and electrons (or negative ions), and the concentration of neutral particles is far greater than the concentration of charged particles so that the plasma is weakly ionized. The concentration of charged particles is such that the ratio of the Debye radius to that of the probe $\alpha = \lambda_D/R << 1$. Chemical reaction in the stream is assumed to be frozen. The probe surface temperature $T_p^0$ is kept constant and less that the temperature of the approach stream $T_\infty^0$. At a distance from the probe there is thermodynamic equilibrium so that the temperatures of charged particles and neutral gas coincide.

Probe operation under these conditions may be described by a set of equations (in dimensionless form) [7]

$$\mathrm{ReSc}\,\rho \mathbf{u}\nabla c_+ - \nabla\left[\rho D_+\left(\frac{c_+}{p_+}\nabla p_+ - \frac{c_+}{T_+}\nabla\psi\right)\right] = 0; \quad (1.1)$$

$$\beta\mathrm{ReSc}\,\rho \mathbf{u}\nabla c_- - \nabla\left[\rho D_-\left(\frac{c_-}{p_-}\nabla p_- + \frac{c_-}{T_-}\nabla\psi\right)\right] = 0; \quad (1.2)$$

$$\alpha^2\nabla^2\psi = \rho(c_+ - c_-). \quad (1.3)$$

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Here Sc $= (\nu/D_+)_\infty$ is Schmidt number ($\nu$ is kinematic viscosity coefficient); $\rho$ is neutral gas density; **u** is velocity field; $c_+$, $c_-$ mass fractions; $p_+$, $p_-$ are partial pressures; $T_+$, $T_-$ are temperatures; $D_+$, $D_-$ are diffusion coefficients for positively and negatively charged particles respectively; $\beta = (D_+/D_-)_\infty$; $\psi$ is electric potential.

Spatial movements are dimensionless in terms of probe radius. Dimensionless electric potential $\psi$ is connected with dimensional potential $\varphi$ by the relationship $\psi = -e\varphi/kT_\infty{}^0$ (e is electron charge, k is Boltzman constant). The rest of the values are related to their values at infinity.

Under real conditions Sc $\sim$ 1 so that the gas dynamic Reynold number is of the same order as the electric number. The connection between gas density and temperature is described by an equation of state

$$\rho T = 1,$$

since due to low gas velocity the change in pressure is ignored. Partial pressures have the form

$$p_+ = c_+\rho T_+,\ p_- = c_-\rho T_-.$$

The temperature of ions in a continuous atmosphere regime equals the neutral particle temperature ($T_+ = T$) [7]. In addition the partial pressure of positive ions $p_+ = c_+$. In order to determine the temperature of electrons in the general case it is necessary to consider an equation for electron energy. In order not to complicate the problem as in [4] we limit ourselves to two particular cases. In the first electrons are also in local thermal equilibrium with the surrounding gas ($T_- = T$, $p_- = c_-$), and this condition is strictly fulfilled if the transfer of a negative charge is accomplished by ions. In the second case the temperature of electrons is frozen and equal to its value at infinity ($T_- = 1$). Then the partial pressure of electrons $p_- = c_-/T$.

It is noted that in the second case in [4] the continuity equation for electrons (1.2) is not written correctly since the density of the electron stream in the general case ($T_- \neq T$) is determined by the gradient of partial pressure and not concentration [7].

The dependence of diffusion coefficients on temperature may be defined by power functions $D_+ = T^m$, $D_- = T^n$. This type of dependence is given in [8] for different gases. In the case of the frozen temperature for electrons a change in $D_-$ is connected with a change in the neutral gas density $D_- = T$ [7]. The ratio of $\beta << 1$ if the negative charge is transferred by electrons, and $\beta = 1$ if negative particles are ions.

Profiles of velocity **u** of a neutral gas due to the low level of ionization are determined from solving the problem for flow round a cylinder by viscous gas and they do not depend on the presence of an ionized component. With Re $<< 1$ they are obtained in [9] by the method of combined asymptotic expansions. If the dependence of thermal conductivity coefficient K for a neutral gas on temperature is a power function $K = T^l$, then the zero term of the asymptotic expansion for temperature close to the probe with $r < O(1/\mathrm{Re})$ is given by the expression

$$T = [T_p^{l+1} - (T_p^{l+1} - 1)\ln r/\ln(1/\mathrm{Re})]^{1/(l+1)}, \tag{1.4}$$

where r is radial coordinate. At a distance from the probe the temperature is close to undisturbed ($T = 1$).

Boundary conditions for Eqs. (1.1)-(1.3) are:
at a distance from the probe with $r \to \infty$

$$c_+ = c_- = 1,\ \psi = 0; \tag{1.5}$$

at the probe surface with $r = 1$

$$c_+ = c_- = 0,\ \psi = \psi_p\ \text{(prescribed)} \tag{1.6}$$

2. The solution of problem (1.1)-(1.6) is obtained first for saturation currents. We give the path of this solution for the case when $T_- = T$.

In order to determine the saturation current, as for the total volt–ampere characteristic, it is not necessary to know in detail the velocity profile for a neutral gas since with Re $<< 1$ convective terms of Eqs. (1.1) and (1.2) may be ignored in the region close to the probe (internal) with $r < O(1/\mathrm{Re})$. Then ignoring in this region the dependence of the function sought on angular coordinate $\theta$ Eqs. (1.1) and (1.2) may be integrated:

$$\frac{dc_+}{dr} - \frac{c_+}{T}\frac{d\psi}{dr} = \frac{I_+ T^{1-m}}{r}; \tag{2.1}$$

$$\frac{dc_-}{dr} + \frac{c_-}{T}\frac{d\psi}{dr} = \frac{I_- T^{1-n}}{r}. \tag{2.2}$$

Here instead of $\rho$ and $D_\pm$ their dependences on temperature are substituted: $I_\pm$ are dimensionless flows at the probe of positively and negatively charged particles.

As is well known, with $\alpha << 1$ in the flow field it is possible to separate a thin layer of a space charge immediately adjacent to the probe surface and a quasineutral region where $c_+ \simeq c_- = c$. In the quasineutral region combining (2.1) and (2.2) and integrating the equation obtained we have

$$c = A_1 - \frac{(l+1)\ln(1/\mathrm{Re})}{2(T_p^{l+1} - 1)}\left(I_+\frac{T^{2-m+l}}{2-m+l} + I_-\frac{T^{2-n+l}}{2-n+l}\right) \tag{2.3}$$

($A_1$ is the integration constant).

Integration is facilitated if in (2.1) and (2.2) we move from variable r to T. Expression (2.3) is an important term of the internal asymptotic expansion of quasineutral concentration c with respect to Reynolds number.

At a distance from the probe with $r > O(1/\mathrm{Re})$ (outer region) it is not possible to ignore convective terms of Eqs. (1.1) and (1.2), but the flow rate as for temperature is close to undisturbed. The quasineutral concentration in this region is given by the expression [3]

$$c = 1 - \exp(\varkappa r\cos\theta)\sum_{m=0}^{\infty} B_m K_m(\kappa r)\cos m\theta, \tag{2.4}$$

where $B_m$ are integration constants; $K_m$ are modified Bessel functions of the second type for order m; $\kappa = (1 + \beta)\mathrm{ReSc}/4$.

Constant $A_1$ in expression (2.3) is found on the basis of asymptotic combination. In order to provide combination it is necessary in (2.4) to assume that $B_1, B_2, \ldots = 0$ in order to exclude the dependence on $\theta$. Further with $\kappa << 1$ taking the first term of the expansion in the series for function $K_0(\kappa r)$ and introducing external variable $s = \mathrm{Re}r$ we obtain an internal representation of external solution (2.4):

$$c = 1 - B_0\{C + \ln[(1+\beta)\mathrm{Sc}/8] + \ln s\} \tag{2.5}$$

($C = 0.5772$ is Euler constant).

Now we obtain an external representation of internal solution (2.3). Turning to variable s in the expression for temperature (1.4) we have

$$T = [1 - (T_p^{l+1} - 1)\ln s/\ln(1/\mathrm{Re})]^{1/(l+1)} \simeq 1 - \frac{T_p^{l+1} - 1}{l+1}\frac{\ln s}{\ln(1/\mathrm{Re})}, \tag{2.6}$$

since with $\mathrm{Re} << 1$ the second term in square bracket is small compared with one.

Substituting (2.6) in (2.3) and comparing the external representation obtained for the internal solution from (2.5) and in accordance with the principal of asymptotic combination [10] we find

$$A_1 = 1 + \frac{I_+ + I_-}{2}\left[C + \ln\frac{(1+\beta)\mathrm{Sc}}{8}\right] + \frac{(l+1)\ln(1/\mathrm{Re})}{2(T_p^{l+1} - 1)}\left(\frac{I_+}{2-m+l} + \frac{I_-}{2-n+l}\right).$$

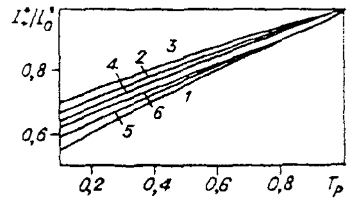


Fig. 1

Now assuming in (2.3) that C = 0 with r = 1 and $I_- \to 0$ we determine the ion saturation current:

$$I^*_+ = \frac{2(1 - T_p^{l+1})}{\{C + \ln[(1 + \beta)Sc/8]\}(T_p^{l+1} - 1) + (l + 1)\ln(1/Re)(1 - T_p^{2-m+l})/(2 - m + l)}. \tag{2.7}$$

The electron saturation current $I^*_-$ is also given by expression (2.7) in which m should be substituted by n.

It is easy to see that at the limit $T_p \to 1$ the saturation current determined by (2.7) tends towards an isothermal value $I_0^*$ obtained in [3]:

$$I^*_0 = \frac{2}{\ln(1/Re) - C - \ln[(1 + \beta)Sc/8]}. \tag{2.8}$$

At the limit Re → 0 the ratio of the current given by expression (2.7) to the isothermal value (2.8) has the form

$$\frac{I^*_+}{I^*_0} = \frac{2 - m + l}{l + 1}\frac{1 - T_p^{l+1}}{1 - T_p^{2-m+l}}. \tag{2.9}$$

We dwell on two particular cases of temperature dependences for the diffusion coefficient of ions and the thermal conductivity coefficient for a neutral gas corresponding to an idealized model for force reaction of molecules. In the first, as also in [4], we use the model of a gas formed by solid spherical particles. For this model m = 3/2, $l$ = 1/2. The dependence of normalized ion saturation current at a cylindrical probe with Re → 0 on probe temperature (2.9) agrees with the corresponding dependence in [4] for a spherical probe in an immobile plasma.

For so-called Maxwellian molecules m = 2, $l$ = 1. The temperature dependence of the diffusion coefficient for ions for this model approaches the real situation more [8]. The dependence of limiting normalized saturation current on temperature with Re → 0, as follows from (2.9), is linear. It is presented in Fig. 1 (line 1) where temperature dependences for normalized saturation current with finite Reynolds numbers (Re = 0.1 and 0.2, curves 2 and 3) and with Sc = 1 for transfer of a negative charge by electron ($\beta << 1$ are also given). Curve 4 relates to the case of transfer of a negative charge by ions ($\beta = 1$) and Re = 0.1. As can be seen from Fig. 1 there is a tendency of an increase in normalized saturation current with an increase in Re and for negative ions this tendency is less manifest.

For the frozen temperature of electrons Eq. (2.2) takes the form

$$T\frac{d}{dr}\left(\frac{c_-}{T}\right) + c_-\frac{d\psi}{dr} = \frac{I_-}{r}.$$

Acting as shown above for the concentration of charged particles in the quasineutral region close to the probe we obtain

$$c = \frac{A_2 T}{1 + T} - \frac{(l + 1)\ln(1/Re)}{(T_p^{l+1} - 1)(1 + T)}\left[I_+\frac{T^{3-m+l}}{2 - m + l} + I\,\frac{T^{l+1}}{l}\right].$$

After carrying out the required more labor-consuming calculations we determine that the constant

$$A_2 = \left\{2 + \frac{(l+1)\ln(1/\mathrm{Re})}{T_p^{l+1} - 1}\left[\frac{I_+}{2 - m + l} + \frac{I_-}{l}\right] + \left[\frac{I_+(5 - 2m + 2l)}{2} + \frac{I_-(2l+1)}{2}\right]\right.$$
$$\left.\times\left(C + \ln\frac{\mathrm{Sc}}{8}\right)\right\}/[1 + (T_p^{l+1} - 1)\left(C + \ln\frac{\mathrm{Sc}}{8}\right)/2(l+1)\ln(1/\mathrm{Re})].$$

The ion saturation current is written as

$$I_+^* = \frac{4(2 - m + l)(1 - T_p^{l+1})}{[C + \ln(\mathrm{Sc}/8)](T_p^{l+1} - 1)(5 - 2m + 2l - T_p^{2-m+l}) + 2(l+1)\ln(1/\mathrm{Re})(1 - T_p^{2-m+l})}.$$

The electron saturation current

$$I_-^* = \frac{4l(1 - T_p^{l+1})}{[C + \ln(\mathrm{Sc}/8)](T_p^{l+1} - 1)(2l + 1 - T_p^l) + 2(l+1)\ln(1/\mathrm{Re})(1 - T_p^l)}.$$

As a check it is possible to see that with $T_p \to 1$ saturation currents tend towards the isothermal value (2.8).

The ion saturation current normalized for the isothermal value, as also for the equilibrium saturation current of electrons, at the limit $\mathrm{Re} \to 0$ is given by expression (2.9), and the normalized electron saturation current with $\mathrm{Re} \to 0$

$$\frac{I_-^*}{I_0^*} = \frac{l}{l+1}\frac{1 - T_p^{l+1}}{1 - T_p^l}. \tag{2.10}$$

For the model of gas consisting of solid spherical particles the results obtained in contrast to the case of a uniform electron temperature do not coincide with results in [4] for a spherical probe in an immobile plasma, which as already noted is connected with the incorrect entry of the electron discontinuity equation in [4] when $T_- \neq T$. If this equation is written correctly, then for a spherical probe in an immobile plasma it is easy to obtained results (2.9) and (2.10).

An interesting result of the present work is the fact that the ion saturation current for the equilibrium and frozen temperatures of electrons in the limiting case $\mathrm{Re} \to 0$ coincide. Divergence occurs with $\mathrm{Re} \neq 0$. The temperature dependence for the normalized ion saturation current for the frozen temperature of electrons and a model gas of Maxwellian molecules are also given in Fig. 1. Curves 5 and 6 relate to $\mathrm{Re} = 0.1$ and 0.4. As can be seen, an increase in saturation current with an increase in Re occurs even slower than for negative ions. Another interesting result is the fact that for the model of a gas of Maxwellian molecules the ion and electron saturation currents coincide, as also for the frozen temperature of electrons.

3. Volt–ampere characteristics may be obtained similar to that for a probe in an isothermal plasma [3]. Here we limit ourselves to the model of a gas of Maxwellian molecules.

For the equilibrium case from (2.1)-(2.3) for the potential in the internal quasineutral region we write

$$\psi = -\lambda(T + 1) - \lambda\frac{A_1}{b}\ln(A_1 - bT)$$
$$(\lambda = (I_+ - I_-)/(I_+ + I_-),\ b = \ln(1/\mathrm{Re})(I_+ + I_-)/(T_p^2 - 1)). \tag{3.1}$$

The integration constant in (3.1) is selected so that with $T \to 1$ the behavior of $\psi$ is the same as for an isothermal plasma [3]. From (3.1) it follows that $\psi \to \infty$ when $T \to T_s = A_1/b$. This occurs when $\xi \to \xi_s = \ln(1/\mathrm{Re})(T_p^2 - T_s^2)/(T_p^2 - 1)(\xi = \ln r)$.

Thus, quasineutral solution (3.1) is only correct for $\xi \to \xi_S$. Analysis of the layer of a space charge with $\xi \lesssim \xi_s$ is similar to [3]. Equation (1.3), (2.1), and (2.2) after transformation may be reduced to a single equation for the field $E = d\psi/d\xi$. Applying to it the transformation

$$\zeta = a\alpha^{-2/3}(\xi - \xi_s),\ E(\xi) = a\alpha^{-2/3}F(\zeta),$$

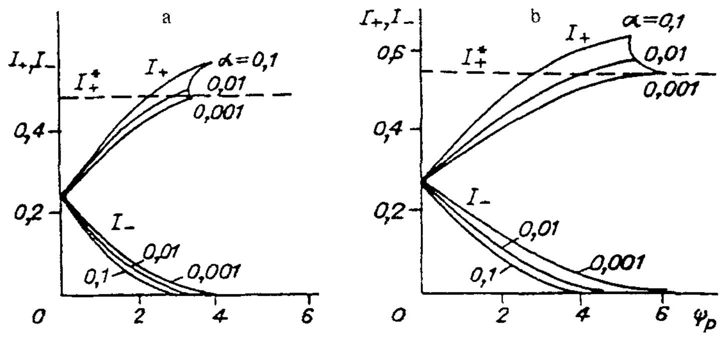


Fig. 2

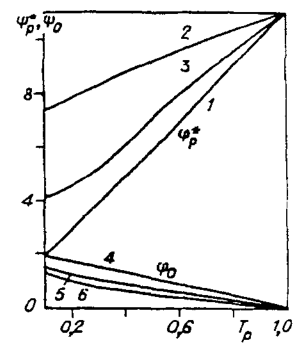


Fig. 3

where $a = \exp(2\xi_s/3)(I_+ + I_-)^{1/3}/T_s^{1/3}$, and ignoring terms of the order $\alpha^{2/3}$, we obtained an equation for F which after integration is written in the form

$$F'' = \frac{F^3}{2T_s^2} + \zeta\frac{F}{T_s^2} + \frac{\lambda}{T_s}. \tag{3.2}$$

Equation (3.2) is an extension of the general equation for the layer of a space charge [11] in the case of an nonisothermal plasma. With $\zeta \to \infty$ the solution of Eq. (3.2) should tend towards quasineutral, which is written as $F \to -\lambda T_s/\zeta$. At the probe surface it is possible to obtain $F_p' = 0$ with $\zeta_p = -F_p^2/2$. Further numerical solution is accomplished by the procedure in [3].

Calculated volt–ampere characteristics for different $\alpha$ with Re = 0.2 and Sc = 1 are presented in Fig. 2a, b ($T_p$ = 0,25 and 0.5 respectively). It can be seen that with a reduction in $\alpha$ the characteristics approach the level of the saturation current. The saturation current sets in sooner, the lower is the probe temperature.

The start of saturation will conditionally be assumed to be the extreme right-hand point of the curve $\alpha = 0.001$. For this point in the calculation $I_-/I_+ = 0$. Probe potential $\psi_p^*$ with which the saturation current is achieved in relation to $T_p$ is presented in Fig. 3 (curve 1). It is possible to write approximately that it is connected with temperature $T_p$ by the relationship $\psi_p^* \simeq 10T_p + 1$. With this potential and quite small $\alpha$ the current at the probe is close to the theoretical saturation point. It is noted that potential $\psi_p^*$ is almost independent of Re in the range when it is suitable for the present study Re $\leq$ 0.4. This procedure may also be repeated for a model gas of elastic spheres. A change in the model also does not affect the value of $\psi_p^*$.

For the frozen temperature of electrons in the internal quasineutral region it is possible to find

$$\psi = \ln\frac{1 + T}{2} + \frac{I_-(T - 1)}{I_+ + I_-} + \frac{A_2 I_- - 2bI_+}{(I_+ + I_-)2b}\ln\left(\frac{A_2}{2} - bT\right).$$

Acting the same as described above, we obtain an analog of Eq. (3.2):

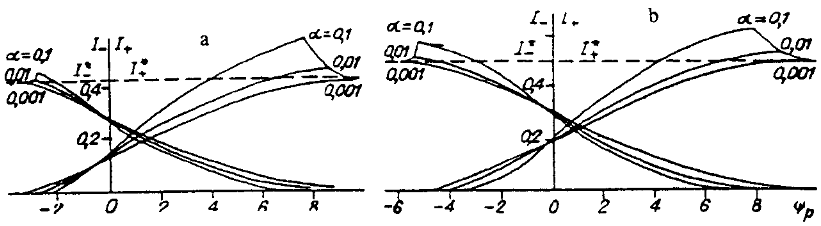

Fig. 4

$$F'' = \frac{F^3}{2T_s} + \zeta\frac{F}{T_s} + \frac{\lambda_1}{T_s} + \left(\frac{1}{T_s} - 1\right)FF' \qquad (3.3)$$
$$(\lambda_1 = (I_+ - T_s I_-)/(I_+ + I_-),\ T_s = A_2/2b).$$

The boundary condition at the probe surface for Eq. (3.3) is unchanged, but with $\zeta \to \infty$, $F \to -\lambda_1/\zeta$.

Calculated characteristics with the same parameters as for Fig. 2 are provided in Fig. 4. In contrast to the case of equilibrium temperature for electrons when probe characteristics are symmetrical with respect to the ordinate axis, for the frozen temperature of electrons the characteristics are markedly asymmetric. With a probe potential equal to that of the plasma $\psi_p = 0$, the dimensionless electron current appear to be greater than the dimensionless ion current. Equality of them occurs with some positive potential $\psi_0$ (the dimensional potential is negative).

Potential $\psi_0$ is greater, the less is $T_p$, and with fixed temperature $T_p$, the less is $\alpha$. Dependences for $\psi_0$ on $T_p$ for different $\alpha$ are given in Fig. 3. Curves 4-6 relate to $\alpha = 0.001$; 0.01; 0.1. Potential $\psi_p^*$ with which saturation is achieved is more conveniently reckoned from $\psi_0$. Temperature dependences of potential $\psi_p^*$ reckoned for the absolute value from $\psi_0$ are given in Fig. 3. Curve 2 corresponds to saturation of the ion current, and 3 to saturation of the electron current. As can be seen saturation of the electron current compared with the ion current occurs with a lower potential.

4. We use the results obtained in order to explain some experimental results with probe measurements in the plasma of a flame.

The experimental characteristics of a cylindrical probe taken in a flame with addition of sodium were given in [3] where it was determined that the potential of the plasma with respect to the burner body is 0.5 V. As follows from the results of the present work, the potential found for the plasma is the same as in the case of the equilibrium temperature of electrons; if it is frozen, then it is not the potential of the plasma, but it is some potential which in dimensionless form is denoted as $\psi_0$ in the preceding section. However, in the experiment in question the equilibrium case is realized.

Dimensionless probe potentials with respect to $\psi_0$ with which currents reach saturation comprised in [3] $\psi_p^* = 5$ for the ion current and $\psi_p^* = 7.5$ for the electron current. These values, which are lower than given by the theory in [3] for an isothermal plasma, are entirely explained within the scope of this work. The greater attention given in [3] to the characteristics shows that saturation of the electron current may also be assumed to set in with $\psi_p^* = 5$, i.e., with approximately the same values of potential which correspond to the case of the equilibrium temperature of electrons. With a flow temperature $T_\infty^0 = 2400$ K saturation of the current with $\psi_p^* = 5$ occurs with a probe temperature $T_p^0 = 950$ K. The probe temperature in the experiment in [3] was not specially measured, but this value is entirely acceptable and it agrees with the results of work where the temperature was measured in [6].

In the experiment in [3] it was noted that the ratio of electron and ion saturation currents was much less than predicted by theory and it was assumed that this is explained by formation of negative ions whose diffusion coefficient is much less than for electrons and of the same order as the diffusion coefficient for positive ions. On the basis of the results of the present work it is possible to confirm that this explanation is entirely possible since if there was break away of the electron temperature from that for heavy particles close to the probe this would not affect the ratio of saturation currents.

Provided in Fig. 5 are examples for the current at the probe with the passage of time as the probe heats up in the flame. Curve 1 is obtained with probe potential $-12$ V with respect to the burner body. As can be seen from Fig. 5, after introducing the probe into the flame the current which with this potential is the current of positive ions is almost unchanged to a certain instant of time after which it increases sharply. This current behavior is well known [6]. Of considerable interest is curve 2 obtained with a weakly negative probe potential with respect to the plasma potential $\varphi_p = -0.5$ V ($\varphi_p = 0$ with respect to the burner body). The path of the curve is complex in nature and it appears that such a record has not been published.

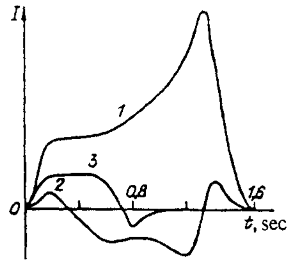


Fig. 5

From the point of view of the present work the path of curve 2 may be explained as follows. Potential $\varphi_p = -0.5$ V corresponds to $\psi_p = 2.5$. In introducing a probe having room temperature $T_p^0 = 300$ K into a flame with a temperature of about 2400 K the saturation current should be observed for the equilibrium temperature of electrons with $\psi_p^* = 2.25$. Thus, in the first instant of time after introducing the probe its potential appears to be greater to be greater than the potential of the ion saturation current. Consequently, current at the probe is entirely determined by the positive ion current. Subsequently as the probe heats up the potential for the start of saturation $\psi_p^*$ shifts in the direction of higher values, and the current at the probe is determined by the current of both positively and negatively charged particles which leads to a gradual reduction in the total current since the relative contribution of negative particles to the probe current gradually increases. It is necessary to consider that the "effective" value of diffusion coefficient for negatively charged particles determined in [3] exceeds approximately by a factor of seven the diffusion coefficient for positive ions. Therefore, although the dimensionless ion current remains greater than the dimensionless electron current the contribution of negatively charged particles to the total dimensional current starts to predominate, which causes a shift in the sign of current. A further increase in current is connected with the start of thermoelectron emission.

Curve 3 in Fig. 5 was obtained with the same conditions as for 2 but for a probe of greater length and thickness. The rate of heating for this probe was the slowest.

In conclusion it is noted that experimental verification of the relationship between the saturation current and the concentration of charged particles provided in [2] showed that there is some increase in the experimentally determined saturation current above the theoretical value. As can be seen, consideration of a nonisothermal plasma leads to a reduction in the theoretical saturation current, and it would appear to a greater divergence between theory and experime
nt. However, with an increase in Re a tendency is noted of an increase in the saturation current normalized for the isothermal value, and in [5] it was established that with Re >> 1 the saturation current for a cooled probe is even somewhat greater than for a cooled probe. Thus, it might be expected that consideration of a nonisothermal plasma does not have a marked effect on the degree of conformity between theory and experiment, the divergence between which may possibly be explained by the combined effect of negative ions [12] and the kinetics of ionization reaction, i.e., recombination of atoms and ions of the additive [13].

## REFERENCES

1. M. S. Benilov and G. A. Tirskii, "Saturation currents at a probe in a dense plasma," Prikl. Mekh. Tekh. Fiz., No. 6 (1979).
2. Z. M. Egorova, A. V. Kashevarov, and N. S. Tskhai, "Ion saturation current at electric probes in plasma streams with low Reynolds numbers," Prikl. Mekh. Tekh. Fiz., No. 1 (1990).
3. Z. M. Egorova and A. V. Kasherov,"Volt–ampere characteristics of a cylindrical Langmuir probe in a slowly moving plasma," Prikl. Mekh. Tekh. Fiz., No. 2 (1993).
4. Chapkis and Baum, "Theory of a cooled spherical electrostatic probe in a continuous gas atmosphere," RTK, **9**, No. 10 (1971).
5. M. S. Benilov, B. V. Rogov, and G. A. Tirskii, "Theoretical determination of ion saturation current at electric probes in subsonic plasma streams," Teplofiz. Vysokikth Temperatur, **19**, No. 5 (1981).
6. M. S. Benilov, B. V. Rogov, and G. A. Tirskii, "Ion saturation current at an electric proben in a slowly moving plasma," Prikl. Mekh. Tekh. Fiz., No. 3 (1982).

7. P. Chan, L. Talbot, and A. Turyan, Electric Probes in Immobile and Moving Plasmas [Russian translation], Mir, Moscow (1978).
8. M. S. Benilov, B. V. Rogov, I. A. Sokolova, and G. A. Tirskii, "Chemical nonequilibrium multicomponent boundary layer of a plasma of molecular gases with an alkaline additive," Prikl. Mekh. Tkh. Fiz., No. 5 (1986).
9. P. F. Hodnett, "Slow compressible flow past a circular cylinder," Phys. Fluids, **11**, No. 8 (1968).
10. M. Van-Dyke, Methods of Disturbance in Fluid Mechanics [Russian translation], Mir, Moscow (1967).
11. I. M. Cohen, "Asymptotic theory of spherical electrostatic probes in slightly ionized collision-dominated gas," Phys. Fluids, **6**, No. 10 (1963).
12. M. S. Benilov, V. F. Kosov, B. V. Rogov, and V. A. Sinel'shchikov, "Saturation currents at electric probes in streams of chemically reacting plasma with different sorts of ions," Teplofiz. Vysokikh Temperatur, **25**, No. 3 (1987).
13. Z. M. Egorova, A. V. Kasherov, and N. S. Tskhai, "Ion saturation current at electric probes in the plasma of a flame with an alkaline addition," Teplofiz. Vysokikh Temperature, **30**, No. 3 (1992).