ON INVESTIGATION OF THE PARAMETERS OF A LOW DENSITY NONEQUILIBRIUM PLASMA BY USING A THERMOANEMOMETER – LANGMUIR PROBE

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Formulas are obtained to determine the fundamental local parameters of a partially ionized low density gas. Results are presented of experimental investigations of a nonisothermal rarefied plasma of a high-frequency discharge in helium at pressures of 0.07, 0.12, and 0.20 mm Hg in the absence of a magnetic field.

For many years Langmuir probes have been used by physicists for the diagnostics of a static gas discharge plasma. The measurement technique using electrical probes in a nonisothermal low-density plasma in the absence of a magnetic field has been worked out well. Their application permit a highly accurate determination of the local plasma parameters such as the charged particle density, the electron temperature and the plasma potential. But the determination of the heavy particle temperature by means of the ionic portion of the probe characteristic is quite difficult or generally impossible. A method based on using a hot-wire thermoanemometer connected simultaneously as a Langmuir probe was proposed in [1] for the determination of an aggregate of local flow parameters of a partially ionized gas, including even the heavy-particle temperature. An energy balance equation, which defines the filament surface temperature T_W as a function of the probe potential, is formed to describe the operation of the thermoanemometer placed in a nonequilibrium low-density plasma.

The energy balance equation in a fixed plasma

$$Q_n + Q_\alpha + J + A\varepsilon\sigma(T_0^4 - T_w^4) = 0$$

is written as [1]

$$\frac{\sqrt{\pi}\,\alpha p_n v_n RL}{2}\,\frac{\gamma+1}{\gamma-1}\left(1-\frac{T_w}{T_n}\right) + Q_\alpha + I_{\text{н}}^2 R_w + 2\pi RL\varepsilon\sigma\left(T_0^4 - T_w^4\right) = 0, \quad (1)$$

where

$$Q_\alpha \equiv Q_e = \frac{I_e}{e}\,(\varkappa + 2kT_e + e|V|)$$

for V > 0;

$$Q_e = \frac{I_e}{e}\,(\varkappa + 2kT_e)$$

for $V \lessgtr 0$;

$$Q_\alpha \equiv Q_i = \frac{I_i}{e}\,[\zeta + \alpha_i(0.5kT_e + e|V|) - \gamma_i\varkappa]$$

for V < 0.

For intermediate potentials on the filament surface evidently $Q_\alpha = Q_e + Q_i$.

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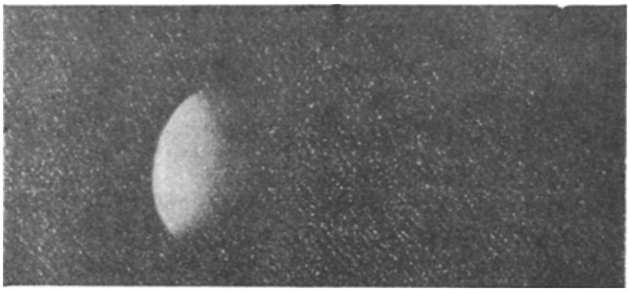

Fig. 1. Glow of the discharge at a 0.12 mm Hg pressure.

The accommodation coefficient α_i in Q_i is introduced so that neutralization of the ions slowly approaching the metal surface would occur mainly at a spacing of several ion diameters. It can therefore be expected that, in the majority of cases, a neutralized ion will reach the metal surface as a neutral molecule. The values of the accommodation coefficients of positive ions in a gas discharge approach the accommodation coefficients of neutrals on a surface covered by an absorbed gas [2-4].

Moreover, the fact that the electrical field of the probe penetrates not only the volume charge domain at high negative potentials, but also the quasineutral plasma, i.e., that the plasma ions arrive at the boundary of the layer near the electrode at a velocity $v_i \gtrless \sqrt{kT_e/m_i}$ directed at the probe, is taken into account in determining Q_i and I_i.

An analysis of the energy balance equation $T_w = T_w(V)$ and the volt–ampere characteristic $I_\Sigma = I_\Sigma(V)$ permits the determination of an aggregate of local parameters of a partially ionized gas.

Thus, after having substituted the electron temperature T_e, the charged particle concentration n_0, and the plasma potential φ_0 found by means of the probe characteristic [3] into (1), we obtain for T_n

$$T_n + \beta^{-1}\left[I_H^2 R_w + 2\pi R L \varepsilon\sigma (T_0^4 - T_w^4) + Q_\alpha\right] T_n^{\frac{1}{2}} - T_w = 0. \tag{2}$$

Here $\beta = \alpha p_n RL(\pi k/2m_n)^{1/2}(\gamma + 1/\gamma - 1)$.

But in forming the energy balance equation we neglected losses due to heat elimination to the fastenings. This is valid if the supports are provided with heaters. Otherwise these losses can be significant and they must essentially be taken into account for more accurate estimates of the final results. The energy balance equation for a unit length of the filament under consideration taking account of the heat transferred to the supports by heat conduction

$$Q_h = \frac{\partial}{\partial x}\left(-\pi R^2 K_w \frac{\partial t_w}{\partial x}\right)$$

is written as

$$\rho_w c_w \pi R^2 \frac{\partial t_w}{\partial t} = \pi R^2\left[K_w \frac{\partial^2 t_w}{\partial x^2} + \frac{dK_w}{dt_w}\left(\frac{\partial t_w}{\partial x}\right)^2\right] + \frac{Q_\alpha}{L} + I_H^2 \frac{R_w}{L} + \frac{\sqrt{\pi}\,\alpha p_n v_n R}{2}\,\frac{\gamma+1}{\gamma-1}\left(1 - \frac{t_w}{T_n}\right) + \frac{A}{L}\,\varepsilon\sigma\,(T_0^4 - t_w^4),$$

where $t_w = t_w(t, x)$ is the local filament temperature at a section with coordinate x; ρ_w, c_w, K_w are the density, specific heat, and coefficient of heat conduction of the filament material. It is hence assumed that the radial temperature gradients are negligible, and the filament diameter and the current density are constants in each section. Since tests are ordinarily conducted in the stationary mode, then $t_w = t_w(x)$ and $\partial t_w/\partial t = 0$. Moreover, it can be assumed with sufficient accuracy that

$$K_w = \text{const},\ t_w^4 - T_0^4 \approx 4t_w T_w^3 - 3T_w^4 - T_0^4 \text{ and } R_w = R_0[1 + \theta(t_w - 273)].$$

Using these simplifications we obtain

$$\pi R^2 K_w \frac{d^2 t_w}{dx^2} + \frac{I_H^2 R_0}{L}[1 + \theta(t_w - 273)] + \frac{\sqrt{\pi}\,\alpha p_n v_n R}{2}\,\frac{\gamma+1}{\gamma-1}\left(1 - \frac{t_w}{T_n}\right) + \frac{Q_\alpha}{L} - 2\pi R\varepsilon\sigma(4t_w T_w^3 - 3T_w^4 - T_0^4) = 0$$

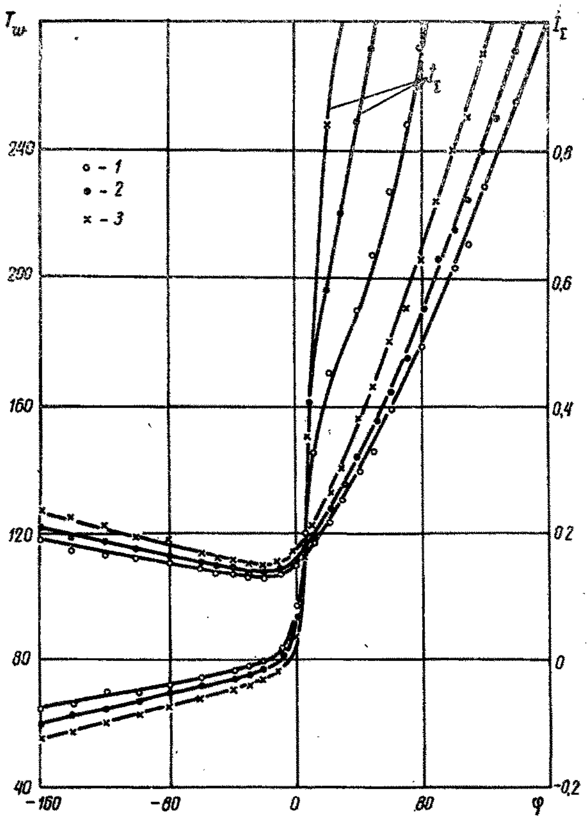

Fig. 2. Graphs of the dependences of the filament surface temperature T_w (°C) and the probe current I_Σ (ma) on the surface potential φ (V): 1) p = 0.07 mm Hg, 2) 0.12; 3) 0.20.

or

$$\frac{d^2t_w}{dx^2} - \omega^2 t_w + \omega_1^2 = 0, \tag{3}$$

where

$$\omega_1^2 = \frac{\alpha p_n v_n}{2\sqrt{\pi}\,K_w R}\,\frac{\gamma+1}{\gamma-1} + \frac{Q_\alpha}{K_w \pi R^2 L} + \frac{6\varepsilon\sigma T_w^4}{K_w R} + \frac{I_н^2 R_0}{K_w \pi R^2 L}\,(1-273\theta) + \frac{2\varepsilon\sigma T_0^4}{K_w R};$$

$$\omega^2 = \frac{\alpha p_n v_n}{2\sqrt{\pi}\,K_w R T_n}\,\frac{\gamma+1}{\gamma-1} + \frac{8\varepsilon\sigma T_w^3}{K_w R} - \frac{I_н^2 R_0 \theta}{K_w \pi R^2 L}.$$

If the constancy of the temperature T_k on both supports is taken as boundary conditions

$$t_w - T_k = 0 \quad \text{for} \quad x = \pm\frac{L}{2},$$

$$\frac{dt_w}{dx} = 0 \quad \text{for} \quad x = 0,$$

then the solutions of (3) yields the temperature distribution along the filament

$$t_w = \left(T_k - \frac{\omega_1^2}{\omega^2}\right)\frac{\operatorname{ch}\omega x}{\operatorname{ch}\frac{\omega L}{2}} + \frac{\omega_1^2}{\omega^2}$$

and determines the losses because of heat elimination to the fastenings

$$Q_k = 2K_w \pi R^2 \left|\frac{dt_w}{dx}\right|_{x=\pm\frac{L}{2}} = 2K_w \pi R^2 \left|\omega\left(T_k - \frac{\omega_1^2}{\omega^2}\right)\operatorname{th}\frac{\omega L}{2}\right|. \tag{4}$$

Then taking account of heat elimination at the ends, T_n is determined from the equation

$$T_n + \beta^{-1}\,[I_{\text{н}}^2 R_w + 2\pi R L \varepsilon \sigma (T_0^4 - T_w^4) + Q_\alpha - Q_k]\, T_n^{1/2} - T_w = 0 \tag{5}$$

by using successive approximations, where the value to T_n found in (2) is used as the first approximation. In the majority of cases, as a rule, 3-4 approximations are required.

The value of T_n found from (5) affords a possibility of estimating the concentration of neutrals n_n and the degree of ionization by means of the measured pressure $p \approx p_n = n_n k T_n$.

Moreover, in a cylindrically symmetric column of partially ionized gas with or without a magnetic field present under the assumption that the ions and electrons in the unperturbed plasma have a Maxwell velocity distribution for constant temperatures T_i and T_e, the following relationship is valid [5]

$$T_e^2 = \frac{\lambda_{en}^2}{\lambda_{in}^2}\,\frac{\varkappa_i}{\varkappa_e}\,(T_i - T_n)\,T_i. \tag{6}$$

The $\varkappa_i$ and $\varkappa_e$ in (6) denote the mean part of the total ion and electron energies, which is lost upon collision with neutrals. The ion temperature T_i is somewhat greater than the temperature of the neutrals T_n, hence it can be considered that the ions lose energy because of elastic collisions and

$$\varkappa_i \approx \frac{8}{3}\,\frac{m_n m_i}{(m_n + m_i)^2}\left(1 - \frac{T_n}{T_i}\right).$$

For electrons, on the other hand, inelastic collisions play the main part at high temperatures, hence $\varkappa_e = \varkappa_e(T_e)$ [5]

If the mean free paths for the electron–neutral and ion–neutral collisions are assumed equal [3]

$$\lambda_{\alpha n} \approx \left(n_n \sigma_{\alpha n} \sqrt{1 + \frac{T_n m_\alpha}{T_\alpha m_n}}\right)^{-1},$$

then (6) is written for $T_n < T_i \ll T_e$ as

$$T_i T_e^2 = \frac{10.66}{\varkappa_e}\,(T_i - T_n)(T_i^2 - T_n^2). \tag{7}$$

Experimental investigations were conducted using a plasmatron with a coaxial system of water-cooled brass electrodes. A high-frequency discharge (at a frequency of 7 MHz) in helium was the plasma source. To simulate the static conditions after ignition of the discharge and leakage of the gas into the source and the working chamber had ceased, the evacuating pumps of the system were disconnected, the pressure was equilibrated, and the discharge burned in a fixed gas. The glow of the discharge from the free endface of the working chamber is shown in Fig. 1.

The cap of the thermoanemometer–Langmuir probe was in the form of a 0.090 mm diameter and 17 mm long molybdenum filament. The filament dimensions were determined by using a laboratory microscope. The filament was welded to massive steel supports of 1.0 mm diameter and 18 mm length. The filament fastenings were also the current and potential leads. The supports of the cap were provided with miniature thermocouples welded to the lower part of the supports 7 mm from the end. Low inertia of the thermocouples was achieved by using a Chromel–Copel wire junction of 0.13 mm diameter. The thermocouple readings were made on M-82 type millivoltmeters. The filament fastenings of the cap as well as the thermocouples, were insulated from possible contact with the plasma by a special covering. Molybdenum glass of the type 3C-5 and epoxy resin were used as coating. The support diameters were enlarged to 1.73 mm after coating.

The thermoanemometer filament is the sensor of a resistance thermometer, hence it was annealed at a temperature 500-700°K in a TS-24 thermostat before the test in order to stabilize the temperature dependence of the resistance, the dependence $R_W = R_W(T_W)$ was found which turned out to be practically linear in the temperature range used: $R_W = 0.33116 + 0.000705(T_W - 273)$. Vacuum oil was used as thermostat liquid. The electrical measuring circuits as well as the lengths of the current and potential leads were identical during both calibration and in the experiment. The filament calibration was verified periodically. Special precautions were taken in order to eliminate harmful thermal emf's in the thermocouple loop. Switching of the current direction was used as a check, as is ordinarily done in potentiometer circuits.

TABLE 1. Influence of Heat Elimination to the Fastenings on the Value of the Temperature of Neutrals, Pressure 0.12 mm Hg

φ, V	T_w, °K	T_{n_1}			T_{n_4}		
		α=0,20	α=0,28	α=0,35	α=0,20	α=0,28	α=0,35
0	384	335	345	353	405	401	400
10	381,5	351	359	365	400	396	395
20	380	350	357	360	398	395	393
30	381	339	350	357	399	396	395
40	382,5	331	346	353	401	397	396
50	383,3	320	335	346	402	399	397
60	384	300	331	339	404	400	400
70	385	300	320	335	405	401	400

The resistance of the thermoanemometer filament was determined by using a high sensitivity thermoanemometric amplifier developed in the Moscow University Scientific-Research Institute of Mechanics. The change in filament resistance was determined to 0.001 ohm accuracy. The measuring circuit is presented in [1].

The experiment was conducted as follows: after the prescribed discharge mode had been established and pressure measurements had been made, the working heating current was passed through the measuring filament to raise the sensitivity and its resistance was determined. Then an arbitrary potential, regulated with respect to ground, was delivered to the filament and two curves $T_W = T_W(V)$ and $I_\Sigma = I_\Sigma(V)$ were recorded as the filament potential changed. The whole procedure was repeated in reverse order, which decreased the probability of random errors.

The cap was mounted 2 mm from the end of the external electrode of the source. It should hence be noted that the filament of the cap was not subjected to any special treatment in the working chamber so that the conditions on its surface corresponded to the usual technical state of the filament material.

The temperature $T_W = T_W(V)$ and probe $I_\Sigma = I_\Sigma(V)$ characteristics are presented in Fig. 2 for the pressures 0.07, 0.12, and 0.20 mm Hg. The presence of a Maxwell electron velocity distribution permitted determination of the electron temperature T_e by the customary method [3].

The plasma potential was determined by means of the electron branch of the probe characteristic $\log I_e \equiv f(V)$ (intersection of the asymptotes) and by the formula

$$\varphi_0 \approx \varphi_{I_\Sigma=0} + \frac{kT_e}{e} \ln\left(0.7\sqrt{\frac{m_i}{m_e}}\right) \tag{8}$$

at a point where the total current in the probe I_Σ was zero.

To determine the charged particle concentration, the electron

$$n_e = \frac{2\sqrt{\pi}\, I_e}{e v_e A} \tag{9}$$

and ion

$$n_i \approx \frac{I_i}{0.43 e A \sqrt{\frac{2kT_e}{m_i}}\, F\left(\eta, \frac{a}{R}\right)}.$$

parts of the volt–ampere characteristic were used. The effective radius of ion collection $F(\eta, a/R)$ was determined by means of the computed curve presented in [6]. The ion part was processed for $\varphi = -60$ V.

TABLE 2. Local Plasma Parameters of a High-Frequency Discharge in Helium

p, mm Hg	T_e, °K	T_n, °K	T_i, °K	$n_e \cdot 10^{-9}$, cm^{-3}	$n_i \cdot 10^{-9}$, cm^{-3}	$n_n \cdot 10^{-15}$, cm^{-3}	φ_0, в	φ_0, V from (8)	$\varkappa_e$	T_k, °K
0,07	70000	400	2500	1,15	1,16	1,69	8	8,2	0,0115	311
0,12	62000	400	2000	1,77	1,68	2,89	10,5	10,5	0,0081	311,8
0,20	50000	400	1300	2,84	2,71	4,83	11,5	11,6	0,0044	314

The temperature of the neutrals was determined by means of (2) for $I_H = 45.5$ ma; $\gamma_i \approx 0.20$; $\alpha_i \approx 0.4$; $h_i = 24.54$ ev; $\varkappa = 4.27$ ev; $\varepsilon = 0.096$; $T_0 = 290°K$; K_W is taken equal to 0.35 [7]. It should hence be noted that there is some uncertainty in the selection of the value of the accommodation coefficient α [2]. The data in Table 1 perfectly clearly indicate the influence of this uncertainty in a first approximation. Subsequent approximations equilibrate the situation: the influence of α on the quantity T_{n_4} is smoothed out as Q_k is taken into account (Eq. (5)).

The investigations conducted show that the proposed method of determining the parameters of a partially ionized low-density gas is sufficiently convenient at gas pressures from 10^{-3} to units mm Hg, when collisionless flow mode conditions are satisfied for the cap filament.

NOTATION

Q_α	is the total quantity of heat transmitted by the charged particles to the filament in unit time;
Q_n	is the quantity of heat transmitted by the neutrals;
J	is the electric heating energy;
A	is the filament surface area;
L	is the filament length;
a	is the radius of the layer near the electrode;
R	is the filament radius;
ε	is the radiation factor;
σ	is the Stefan-Boltzmann constant;
k	is the Boltzmann constant;
T_0	is the wall surface temperature of the working section of the installation;
p_n	is the gas pressure;
V	is the potential difference run through by a particle in the layer;
γ	is the ratio of the specific heats of the gas;
$\varepsilon = h_i - \varkappa$	is the difference between the ionization energy and the work of the electron yield;
γ_i	is the secondary emission coefficient;
T_{n_1}, T_{n_4}	are the temperature of neutrals, first and fourth approximations;
$\sigma_{\alpha,n}$	is the effective elastic collision cross section of neutrals with respect to ions and electrons;
R_W	is the filament resistivity;
$\eta = eV/kT_e$	is the ratio between the probe's electrical field energy and the electron kinetic energy.

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