International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 3 (2015) pp. 6459-6465

http://www.ripublication.com

Experimental Analytical Study Of Parameters Of A Discharge Positive Column In Mixture He - Hg

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Abstract

The article gives results of probe measurements of parameters of a discharge positive column in gas mixture He - Hg under medium pressures. For the same conditions the author calculated the function of electron distribution by velocities taking into account elastic and non-elastic collisions of electrons with gas mixture atoms and found average energy and drift velocity for electrons. Gas mixture parameters estimation results are compared with data obtained from the probe measurements. The article covers the case when the main component of a mixture is helium, and mercury is given in the form of a minor additive.

Key words. Distribution function, probe methods, velocity, energy, concentration, temperature, elastic, non-elastic.

Introduction

Probe methods [1,2] are widely used for measuring electrokinetic characteristics of gas-discharge plasma of low, high and medium pressures, including also energy characteristics of electron distribution function [3.4].

Improvement of technology and theory of probe research methods are covered by a range of articles and monographs [5-7]. These works review probe methods, analyze their possibilities, study the matters of theoretical interpretation of probe measurements results. Main attention there is given to definition of such parameters like distribution function, concentration and temperature of electrons. It is shown that information on such parameters is obtained from analysis of probe characteristics. It should be noted that notwithstanding many works on research of gas-discharge plasma, nowadays there is no clear guidance which consistently lays out methods of calculation of the function of electrons distribution by velocities. Therefore any refining research can make its contribution to this school development. In this regard both experimental and analytical works on researching of the function of electrons distribution by velocities taking into account elastic and non-elastic collisions of electrons with gas mixture atoms are quite topical.

Methods.

Experimental estimation of parameters of plasma in gas mixture He – Hg was carried out in a discharging tube similar to the one described in the work [8]. The discharging tube diameter was 25 mm. Mercury vapour pressure was estimated with the help of the temperature of a spur with mercury dipped into a water bath. Four cylindrical probes brazed into the discharging tube, located along the tube axis, helped to estimate probe characteristics. Electrons' temperature was estimated using two-probes method, and concetration – using electronic part of the one-probe characteristics. The longitudinal electric field's intensity was estimatedwith the help of compensation method. The research was conducted under helium pressure 1 mm Hg, and mercury pressure 10^{-3} mm Hg. Discharging current strength was changing with the limits of 20 ÷ 100 mA. In course of all tests a homogeneous visible fluorescence was observed, and that speaks for electrophoresis effect's insignificance under the test conditions. Results of probe measurements of concentration and temperature of electrons are shown in the table.

Main part.

As is known, [9], a kinetic equation for the isotropic part of the function of electrons' distribution by velocities $\varphi_o(x)$, takes the following form in case of a constant electric field, ignoring diffusion:

$$-\frac{4}{3}\gamma^2\frac{d}{dx}\left(x\lambda^*\frac{d\varphi_O}{dx}\right)=2\frac{m}{M}u_O{}^2\frac{d}{dx}\left(\frac{x^2}{\lambda^*}\varphi_O\right)-\frac{xu_O{}^2}{\lambda_{н.у.}}\varphi_O\ , \qquad (1)$$

where $\gamma=\dfrac{eE}{m}$, $\lambda^*=\dfrac{1}{ns^*}$ - is an electrons free path diffusion dinstance, $\lambda_{н.у.}=\dfrac{1}{ns_{н.у.}}$ - is a free path distance connected with non-elastic collisions, n is an atoms concentration, e and m are charge and weight of an electron, M is an atomic mass. In equation (1) instead of electron velocity υ the variable $x=\dfrac{\upsilon^2}{u_O}$ was introduced, where $u_O=\dfrac{2e}{m}U_O$, $U_O=19.5\ eV$ is the first helium critical potential.

For an effective section of elastic (s) and non-elastic ($s_{n.e.}$) scattering of electrons with atoms of helium and mercury the following approximations were accepted:

for helium

$$\left.\begin{array}{l} \text{under } x < 0.24,\ s = s_O \\ \text{under } x > 0.24,\ s = \dfrac{0.49 s_O}{\sqrt{x}} \\ \dfrac{n_1 s_O}{p_1} = 18\dfrac{\text{cm}^2}{\text{cm}^3\text{mm Hg}} \end{array}\right\} \quad (2)$$

$$\left.\begin{array}{l} \text{under } x < 1,\ s_{n.e.}^{He} = 0 \\ \text{under } x > 1,\ s_{n.e..}^{He} = s_{On.e.}^{He} \cdot (x-1)\sqrt{x} \\ \dfrac{n_1 s_O}{p_1} = 1.3\dfrac{\text{cm}^2}{\text{cm}^3\text{mm Hg}} \end{array}\right\}, \quad (3)$$

for mercury

$$\left.\begin{array}{l} \text{under } x < 0.24,\ s_{\text{n.e.}}^{\text{Hg}} = 0 \\ \text{under } x > 0.24,\ s_{\text{n.e.}}^{\text{Hg}} = s_{\text{n.e.}}^{\text{Hg}} \cdot \sqrt{x} \\ \dfrac{n_2 s_{On.e.}}{p_1} = 30\dfrac{\text{cm}^2}{\text{cm}^3\text{mm Hg}} \end{array}\right\}, \quad (4)$$

Here n_1, p_1 and n_2, p_2 are atoms concentration and partial pressure of helium and mercury correspondingly.

Relation between effective section for momentum transfer s^* and effective cross section of scattering s will be $s^* = 0.8s$ [9].

Section of elastic scattering of electrons with mercury atoms will be neglected throughout the whole variation interval x.

According to approximations (2) - (4), in the area $0 < x < 0.24$ equation (1) takes the following form

$$\frac{d}{dx}\left(x\frac{d\varphi_O}{dx}\right) + \alpha\frac{d}{dx}\left(x^2\varphi_O\right) = 0, \quad (5)$$

where

$$\alpha = \frac{3}{2}\cdot\frac{\dfrac{m}{M}\cdot\left(0.8\cdot n_1 s_O\right)^2\cdot u_O^2}{\left(\dfrac{e}{m}\right)^2 E^2} = 270\left(\frac{p_1}{E}\right)^2$$

Here E is an electric field intensity in V/cm.

Solution of equation (5) is as follows

$$\varphi_0(x) = e^{-\frac{\alpha x^2}{2}} \cdot \left[D - C\int_0^x \frac{e^{\frac{\alpha}{2}t^2}}{t}dt \right], \tag{6}$$

where C and D are constants.

In the area 0.24 < x < 1 equation (1) takes the form

$$\frac{d}{dx}\left(x^{3/2} \frac{d\varphi_O}{dx} \right) + 0.24 \cdot \alpha \cdot \frac{d}{dx}\left(x^{3/2}\varphi_O \right) - \beta_2 x^{3/2}\varphi_O = 0, \tag{7}$$

where

$$\beta_2 = \frac{3}{4} \cdot \frac{0.49 \cdot 0.8 \cdot n_1 s_O \cdot n_2 s^{Hg}_{\text{Он.у.}} \cdot u_O^2}{\left(\frac{e}{m}\right)^2 \cdot E^2} = 2.5 \cdot 10^5 \frac{p_1 p_2}{E^2}.$$

After transformation of equation (7) we have

$$\frac{d^2\varphi_O}{d\ x^2} + \left(\frac{3}{2x} + 0.24\alpha \right)\frac{d\varphi_O}{dx} + \left(0.24\frac{3 \cdot \alpha}{2x} - \beta_2 \right)\varphi_O = 0, \tag{8}$$

Substitution of $\varphi_O = x^{-\frac{3}{4}} \cdot e^{-0.12\alpha x} \cdot y$ brings this equation to the form

$$y'' - \left[\beta_2 + 0.0144\alpha^2 + \frac{39}{16x^2} - 0.09\frac{\alpha}{x} \right] y = 0, \tag{9}$$

For simplification of the problem, variables 39/16x^2 and 0.09α/x will be replaced by their average values in the involved area of change of x. Then, instead of equation (9), we will have

$$y'' - \left[\beta_2 + 1.44 \cdot 10^{-2}\alpha^2 + 0.21 - 0.22\alpha \right] y = 0, \tag{10}$$

The solution of equation (10) will be

$$y = \sqrt{x}\left[AI_{\frac{1}{2}}\left(\sqrt{a} \cdot x\right) + BK_{\frac{1}{2}}\left(\sqrt{a} \cdot x\right) \right],$$

where α = β_2 + 1.44·10^{-2}α^2 + 0.21 − 0.22α, $I_\nu(x)$ is a Bessel function of an imaginary argument, $K_\nu(x)$ is a Macdonald function [10], A and B are constants.

Thus, in the area 0.24< x <1 for distribution function we have

$$\varphi_O(x) = x^{-\frac{1}{4}} \cdot e^{-0.12\alpha x} \cdot \left[AI_{\frac{1}{2}}\left(\sqrt{a} \cdot x\right) + BK_{\frac{1}{2}}\left(\sqrt{a} \cdot x\right) \right], \tag{11}$$

In the area x >1 equation (1) takes the form

$$\frac{d^2\varphi_O}{d\ x^2} + \left(\frac{3}{2x} + 0.24\alpha \right)\frac{d\varphi_O}{dx} - \left[\beta_2 - 0.36\frac{\alpha}{x} + \beta_1(x-1) \right]\varphi_O = 0, \tag{12}$$

where

$$\beta_1 = \frac{3}{4}\cdot\frac{0.49\cdot 0.8\cdot \mathrm{n}_1 s_{\mathrm{O}}\cdot \mathrm{n}_1 s^{He}_{\mathrm{Он.у.}}\cdot u_{\mathrm{O}}^2}{\left(\frac{e}{m}\right)^2\cdot E^2} = 1.1\cdot 10^4\left(\frac{P_1}{E}\right)^2$$

Substitution of $\varphi_{\mathrm{O}} = x^{-\frac{3}{4}}\cdot e^{-0.12\alpha x}\cdot y$ brings equation (12) to the form

$$y'' - \left[\beta_1(x-1)+\beta_2+(0.12\alpha)^2+\frac{39}{16x^2}-\frac{0.18\alpha}{x}\right]y = 0.$$

Taking into account that $\beta_2 >> \alpha$, $\beta_1 >> \alpha$, $\alpha >> 1$, variable members $39/16x^2$ and $0.18\alpha/x$ will be substitued with their values under $x = 1$. Then we will obtain

$$y'' - [\beta_1(x-1)+\beta_2+(0.12\alpha)^2+2.44-0.18\alpha]y = 0, \tag{13}$$

The solution of equation (13), vanishing under $x \to \infty$, is

$$y = C_1\sqrt{z}\cdot K_{\frac{1}{2}}\left(\frac{2}{3\beta_1}z^{\frac{3}{2}}\right), \tag{14}$$

where

z = $\beta_1(x-1)+\beta_2+(0.12\alpha)^2+2.44-0.18\alpha$.

Thus, in the area $x > 1$ for distribution function we have

$$\varphi_{\mathrm{O}}(x) = C_1 x^{-\frac{3}{4}}\cdot e^{-0.12\alpha x}\cdot\sqrt{z}\cdot K_{\frac{1}{3}}\left(\frac{2}{3\beta_1}z^{\frac{3}{2}}\right), \tag{15}$$

With the help of formulas (6), (11) and (15) we calculated the function of electrons distribution by velocities for conditions corresponding to our experiment. Constant coefficients A, B, C and D were estimated via condition of continuity of functions $\varphi_o(x)$ and $\varphi'_o(x)$ at points $x = 0.24$ and $x = 1$ a, constant C_1 – via condition of normalization of function $\varphi_o(x)$

Transition of the function of electrons distribution by velocities $\varphi_o(x)$ to distribution by energies F(x) is performed using the correlation [9]

$$F(x)dx = a\sqrt{x}\varphi_{\mathrm{O}}(x)dx, \tag{16}$$

where a is a constant coefficient.

Average electrons energy is calculated with the help of expression

$$\bar{x} = \frac{\int_0^\infty xF(x)dx}{\int_0^\infty F(x)dx}, \tag{17}$$

To calculate temperature of obtained distributions a certain effective temperature T_2 should be introduced and connected with the average electrons energy in the usual way.

Comparison of calculated values of temperatures T_2 with the electron gas temperature T_1, which was calculated using the probe method, is represented in the table.

Electrons drift velocity, taking into account distribution function $\varphi_o(x)$, was estimated according to relation [11]

$$\bar{u} = -\frac{1}{3}\sqrt{\frac{2e}{mU_0}} \cdot E \cdot \frac{\int_0^\infty \lambda^* \cdot x \cdot \frac{d\varphi_0}{dx} dx}{\int_0^\infty F(x) dx} , \qquad (18)$$

If you know velocity of drift of electrons and their concentration distribution over discharging tube section, you can find electrons concentration on tube axis for each discharging current value. According to [8], electrons concentration along the discharging tube section is distributed in conformity with the law

$$n_r = n_O I_O\left(2.4\frac{r}{R}\right) , \qquad (19)$$

where R is a discharging tube radius, $I_o(x)$ is a Bessel function of zero-order.

The table shows calculated values of drift velocities ū and electrons concentration on the tube axis n_2 for the same experimental conditions.

Table Experimental and calculated data of parameters of mixture He-Hg

I, mA	E, V/cm	$T_1 \cdot 10^{-3}$ °K	$T_2 \cdot 10^{-3}$ °K	$\bar{u} \cdot 10^{-3}$	$n_1 \cdot 10^{-10}$	$n_2 \cdot 10^{-10}$
20	4.00	43.0	45.0	3.50	0.9	1.7
50	4.25	45.0	46.7	3.70	3.0	4.0
75	4.30	47.0	47.0	3.78	6.0	5.9
100	4.35	48.0	47.5	3.82	8.0	7.8

In the table you can see that there is a satisfactory fit of calculated values of temperature T_2 and concentration n_2 of electrons with their values obtained via probe measurements T_1 and n_1.

Conclusion

Calculations results go to prove that average energy and velocity of electrons drift in a positive column of a discharge of gas mixture He – Hg under conditions we studied can be estimated with satisfactory accuracy, with the help of the function of electrons distribution by velocities, calculated taking into account elastic and non-elastic collisions of electrons with gas mixture atoms.

Resume

With the help of probe characteristics of the positive column of the discharge of gas mixture He – Hg, electrons concentration and temperature were calculated.

We estimated the function of electrons distribution by velocities taking into account elastic and non-elastic collisions of electrons with atoms of mixture He - Hg.

On the basis of the function of electrons distribution by velocities we calculated average energy and drift velocity of electrons in mixture He - Hg.

Calculated data on concentration and temperature of electrons are in a satisfactory fit with these parameters values obtained via probe measurements.

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