# Influence of Nonequilibrium Plasma Parameters on the Value of Negative Anode Potential Drop in a Gas Discharge

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**Abstract – Parameter G is examined which determines the value of anode potential drop and is equal to ratio of current density of electrons penetrating from plasma into the space charge layer surrounding the anode, to discharge current density on the anode. The interval of possible values of this parameter is determined. On the basis of model of nonequilibrium plasma with electron velocity distribution as the sum of distributions of three electron groups (thermal and hot electrons with Maxwellian velocity distributions and the electron beam with velocity distribution which may be resolved into a drift velocity normal to the anode surface and a random motion with a Maxwellian distribution) expressions allowing to calculate negative anode potential drop are obtained. Calculated and experimental results are compared. On the basis of the offered model the influence of parameters of nonequilibrium plasma on the value of negative anode potential drop is investigated.**

## 1. Introduction

In plasma sources of charged particles with large cross-section beams [1-3] emitting plasma is usually created by gas discharges of low pressure whose value in many cases does not exceed ~ 0,1 Pa. At such pressures and anodes of large enough area, which are used in these discharges, potential drop at the anode is usually negative, and its value under certain conditions can reach tens of volts [4-7].

The value of negative anode potential drop is to be taken into account in the organization of electron and ion emission from such volumetric gas discharges. In particular, if electron emission is carried out through the grid emission electrode, which has an anode potential, the value of negative anode potential drop and the corresponding width of electrode layer are to be taken into account when choosing the sizes of cells in a grid emission electrode to maintain grid stabilization of emission current [8]. The negative anode potential drop value determines the shape of current-voltage characteristic of the electronic collector in gas discharge [9] and value of emission current of the plasma cathode [3,5,8]. Besides, the sign and value of anode potential drop influence the operating modes of ionic devices of various types [10].

In many cases of low-pressure gas discharges the mean free path of electrons, accelerated in cathode potential drop or in a double electric layer, exceeds the characteristic sizes of area in which plasma is created. Therefore some fast electrons cannot relax in one flight through this area, and the electronic component of plasma will have nonequilibrium velocity distribution. The present paper is devoted to researching the influence of such nonequilibrium plasma parameters on the value of negative anode potential drop.

## 2. Parameter G

It is known [11] that the value of anode potential drop $U_a$ is determined principally by parameter $G$ which is equal to the ratio of current density $j_e$ of electrons penetrating from plasma into the space charge layer surrounding the anode, to discharge current density on the anode $j_a$: $G = j_e / j_a$. If ionic current on the anode is neglected, for plasma with equilibrium (Maxwellian) electron velocity distribution at negative anode potential drop

$$U_a = \frac{kT_e}{e} \ln G, \tag{1}$$

where $e$ is the electron charge, $k$ is Boltzmann's constant, $T_e$ is the electron temperature.

Let's try to find out what parameter $G$ value depends on and to determine the interval of possible values of this parameter.

In the glow discharge with the cold cathode in view of equality of cathode and anode currents ($j_c S_c = j_a S_a$, where $j_c$ is the cathode current density, $S_c$ and $S_a$ are the cathode and the anode areas)

$$\begin{aligned} G &= \frac{j_e S_a}{j_c S_c} = \frac{j_e S_a}{(j_{ci} + j_{ce}) S_c} = \\ &= \frac{e n_a (kT_{ea} / 2\pi m)^{1/2} S_a}{0{,}4 e n_c (2kT_{ec} / M)^{1/2} (1+\gamma) S_c} = \\ &= \frac{1}{0{,}8\sqrt{\pi}(1+\gamma)} \cdot \frac{n_a}{n_c} \sqrt{\frac{T_{ea} M}{T_{ec} m}} \frac{S_a}{S_c} \approx \\ &\approx 0{,}64 \frac{n_a}{n_c} \sqrt{\frac{T_{ea} M}{T_{ec} m}} \frac{S_a}{S_c}, \end{aligned} \tag{2}$$

where $j_{ci}$ and $j_{ce}$ are the ionic and electronic components of a cathode current density, $n_a$, $n_c$ are the plasma concentrations near the anode and the cathode, $T_{ea}$, $T_{ec}$ are the temperatures of plasma electrons near

the anode and the cathode, $m$, $M$ are the electron and ion masses, $\gamma$ is the coefficient of ion-electron emission (in the glow discharge at discharge voltage some hundreds of volts $\gamma \sim 0{,}1$).

For plane-parallel discharge system ($S_a$=$S_c$) in case of homogeneous distribution of plasma parameters on a positive column of the discharge ($n_a$=$n_c$, $T_{ea}$=$T_{ec}$)

$$G \approx 0{,}64\sqrt{M/m}\,. \qquad (3)$$

Authors of other papers make similar conclusions. A.V. Zharinov and Yu.A. Kovalenko [9] consider $G \sim (M/m)^{1/2}$. In [12] on page 340 $U_a$ expression is received not through parameter $G$ but through other considerations. If this expression is compared with (1), the formula for $G$ will differ from (3) only in numerical factor: it will be 0,41 instead of 0,64.

For the discharge with hollow cathode under condition of plasma homogeneity

$$G \approx 0{,}64\sqrt{\frac{M}{m}}\frac{S_a}{S_k}\,. \qquad (4)$$

A similar expression with numerical factor 0,658 is used in [13] for the indicated geometry. When such a discharge is used as the plasma cathode with exit of electrons through the emission electrode, which is placed under the anode potential, the optimum relation of anode and cathode areas is [14,15,7]

$$S_a/S_k \sim \sqrt{m/M}\,. \qquad (5)$$

When condition (5) is observed $G$ is approximately equal to 1.

Experimental results presented in [6,7] show that, besides the above mentioned parameters, $G$ value can be essentially influenced by the beam of ions penetrating from the outside into the hollow cathode discharge through the grid anode. In this case the value of negative anode potential drop increases up to some tens of volts.

Now we shall estimate $G$ for the discharge with thermionic cathode, functioning in a regime of space charge limited current. In this case, unlike the discharge with the cold cathode, the basic share of cathode current is made not by ions coming on the cathode, but by electrons emitted by the cathode. And the ratio $j_{ce}$ to $j_{ci}$, as is known [16], looks as follows:

$$j_{ce}/j_{ci} \sim \sqrt{M/m}\,. \qquad (6)$$

Then

$$G = \frac{j_e S_a}{(j_{ci}+j_{ce})S_c} \approx \frac{1}{0{,}8\sqrt{\pi}}\cdot\frac{n_a}{n_c}\sqrt{\frac{T_{ea}}{T_{ec}}}\frac{S_a}{S_c} = $$
$$= 0{,}705\frac{n_a}{n_c}\sqrt{\frac{T_{ea}}{T_{ec}}}\frac{S_a}{S_k}. \qquad (7)$$

From comparing (2) and (7) it follows that in the discharge with thermionic cathode, functioning in the regime of space-charge limited current, the value of parameter $G$ is approximately $(M/m)^{1/2}$ times less than in the discharge with the cold cathode, all other factors being the same. In an intermediate case, when thermionic cathode functions in a regime of current saturation and $\gamma$-processes on the cathode become essential alongside with thermionic emission, apparently, parameter $G$ should accept values, intermediate between (2) and (7). Under such conditions as cathode temperature decreases, parameter $G$ should increase. We have found experimental confirmation to it in [4,17]. In our estimations made on the basis of researches of the discharge with thermionic cathode in flat geometry [17], as heating power of cathode decreased, the value of $G$ increased from 4 up to 7. From the results of [4] it follows that in discharge system with cylindrical geometry (axial thermionic cathode and cylindrical anode) as heating power of cathode decreased, the value of $G$ increased from 5 up to 40 and more.

Thus, parameter $G$ can have values from 1 up to some hundreds for plasma with equilibrium velocity distribution of electrons. There are no reasons to consider that these limits will be essentially different for nonequilibrium plasma. The introduction of this parameter allows to abstract from concrete geometry of the discharge system, the kind of working gas, the distribution of plasma parameters on the discharge volume, the type of cathode, the influence of some external factors and to investigate the influence of nonequilibrium plasma parameters near the anode on the value of negative anode potential drop.

## 3. Negative anode potential drop for nonequilibrium plasma

In the present paper the model of nonequilibrium plasma with electron velocity distribution as the sum of distributions of three electron groups is considered. The first two groups (thermal and hot electrons) have concentrations $n_{et}$ and $n_{eh}$ and Maxwellian velocity distributions with temperatures $T_{et}$ and $T_{eh}$ ($T_{et} < T_{eh}$). The third group consists of the electron beam with concentration $n_{eb}$ and velocity distribution whitch may be resolved into a drift velocity $v_o$ normal to the anode surface and a random motion with a Maxwellian distribution with temperature $T_{eb}$. Such an approximation of nonequilibrium electron velocity distribution was used earlier in [17,18].

In view of the accepted electron velocity distribution

$$G = \frac{j_{et}+j_{eh}+j_{eb}}{j_{at}+j_{ah}+j_{ab}}, \qquad (8)$$

where current densities of the thermal $j_{et}$, hot $j_{eh}$ and beam $j_{eb}$ electrons, penetrating from plasma into the anode space charge layer, and also corresponding current densities $j_{at}$, $j_{ah}$, $j_{ab}$ of electrons, arriving on the anode, can be presented as follows:

$$j_{et} = en_{et}\sqrt{\frac{kT_{et}}{2\pi m}}, \qquad j_{eh} = en_{eh}\sqrt{\frac{kT_{eh}}{2\pi m}},$$

$$j_{eb} = en_{eb}\sqrt{\frac{kT_{eb}}{2\pi m}}\exp\left(-\frac{mv_0^2}{2kT_{eb}}\right)+$$

$$+en_{eb}v_0\left\{\frac{1}{2}+\sqrt{\frac{m}{2\pi kT_{eb}}}\int_0^{v_0}\exp\left[-\frac{m(v-v_0)^2}{2kT_{eb}}\right]dv\right\},$$

$$j_{at} = j_{et}\exp\left(-\frac{eU_a}{kT_{et}}\right), \quad j_{ah} = j_{eh}\exp\left(-\frac{eU_a}{kT_{eh}}\right), \qquad (9)$$

$$j_{ab} = en_{eb}\sqrt{\frac{kT_{eb}}{2\pi m}}\exp\left[-\frac{m\left(\sqrt{\frac{2eU_a}{m}}-v_0\right)^2}{2kT_{eb}}\right]+$$

$$+en_{eb}v_0\left\{\frac{1}{2}+\sqrt{\frac{m}{2\pi kT_{eb}}}\int_{\sqrt{\frac{2eU_a}{m}}}^{v_0}\exp\left[-\frac{m(v-v_0)^2}{2kT_{eb}}\right]dv\right\}.$$

Let's introduce the notation:

$$n_e = n_{et}+n_{eh}+n_{eb},$$

$$\alpha_t = \frac{n_{et}}{n_e}, \quad \alpha_h = \frac{n_{eh}}{n_e}, \quad \alpha_b = \frac{n_{eb}}{n_e},$$

$$\beta_h = \sqrt{\frac{T_{et}}{T_{eh}}}, \quad \beta_b = \sqrt{\frac{T_{et}}{T_{eb}}}, \quad W_a = \sqrt{\frac{eU_a}{kT_{et}}},$$

$$x = \sqrt{\frac{m}{2kT_{eb}}}(v_0 - v), \quad x_0 = \sqrt{\frac{m}{2kT_{eb}}}v_0. \qquad (10)$$

Taking into account (10), expression (8) can be presented as

$$G = \frac{\alpha_t + \frac{\alpha_h}{\beta_h} + \frac{\alpha_b}{\beta_b}\Phi_0}{\alpha_t\exp\left(-W_a^2\right)+\frac{\alpha_h}{\beta_h}\exp\left(-\beta_h^2W_a^2\right)+\frac{\alpha_b}{\beta_b}\Phi_a}, \qquad (11)$$

where

$$\Phi_0 = \exp\left(-x_0^2\right)+\sqrt{\pi}x_0\beta_b^2\left[1+\frac{2}{\sqrt{\pi}}\int_0^{x_0}\exp\left(-x^2\right)dx\right],$$

$$\Phi_a = \exp\left[-\left(x_0-\beta_bW_a\right)^2\right]+$$

$$+\sqrt{\pi}x_0\beta_b^2\left[1+\frac{2}{\sqrt{\pi}}\int_0^{(x_0-\beta_bW_a)}\exp\left(-x^2\right)dx\right]. \qquad (12)$$

With the help of the received expressions the negative anode potential drops $U_a$ are calculated for the experimental conditions presented in [4,17] (tables 1 and 2).

Values of $T_{et}$ and $T_{eh}$ in Table 2 were determined by the author of [17]. Other parameters of nonequilibrium plasma are determined by the methods proposed by I. Langmuir [18] and S.D. Gvozdover [17]. Satisfactory concurrence of measured and calculated values $U_a$ confirms the correctness of the proposed model.

Table 1. Comparison of measured and calculated values $U_a$ for cylindrical discharge system with axial thermionic cathode. Numbers of columns correspond to numbers of experimental curves on Fig. 13 [4]

| Parameters | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| G | 5 | 10 | 21 | 40 |
| $n_{et}$, $10^{15}$, m$^{-3}$ | 0,66 | 8,12 | 21,53 | 63,30 |
| $n_{eh}$, $10^{15}$, m$^{-3}$ | 1,61 | 1,54 | 2,73 | 1,05 |
| $n_{eb}$, $10^{13}$, m$^{-3}$ | 4,72 | 3,09 | 1,49 | — |
| $T_{et}$, eV | 11,11 | 2,97 | 2,46 | 2,04 |
| $T_{eh}$, eV | 18,65 | 16,60 | 11,27 | 13,59 |
| $T_{eb}$, eV | 0,28 | 0,45 | 0,40 | — |
| $mv_o^2/2$, eV | 72,9 | 59,5 | 57,5 | — |
| $U_a$, V, Experiment | 42,9 | 25,2 | 18,9 | 8,7 |
| $U_a$, V, Calculation | 43,7 | 26,6 | 19,2 | 9,7 |

Table 2. Comparison of measured and calculated values $U_a$ for discharge system with the flat anode and thermionic cathode. Numbers of columns correspond to numbers of figures with experimental curves in [17]

| Parameters | 3 | 4 | 5 |
|---|---|---|---|
| G | 4,1 | 6,2 | 6,6 |
| $n_{et}$, $10^{16}$, m$^{-3}$ | 0,70 | 1,17 | 1,32 |
| $n_{eh}$, $10^{14}$, m$^{-3}$ | 3,61 | 1,97 | 1,08 |
| $n_{eb}$, $10^{12}$, m$^{-3}$ | 5, 01 | 4,58 | 3,67 |
| $T_{et}$, eV | 1,47 | 1,34 | 1,21 |
| $T_{eh}$, eV | 5,34 | 8,19 | 14,66 |
| $T_{eb}$, eV | 0,56 | 0,54 | 0,77 |
| $mv_o^2/2$, eV | 25,0 | 40,6 | 56,2 |
| $U_a$, V, Experiment | 1,5 | 2,6 | 2,8 |
| $U_a$, V, Calculation | 2,4 | 2,7 | 2,5 |

On the basis of the developed model the influence of various parameters of nonequilibrium plasma on the value of negative anode potential drop was analyzed. To find out the influence of hot electrons and beam electrons on $U_a$, separately from each other, it is advisable to consider two special cases differing in the structure of plasma electronic component: 1) a combination of thermal and hot electrons ($n_{eb}$ = 0), 2) a combination of thermal and beam electrons ($n_{eh}$ = 0). The results of calculation are shown on Fig. 1 and 2 for the first case and on Fig. 3 and 4 for the second case.

As one would expect, as concentration and energy of hot and beam electrons increase, negative anode potential drop increases.

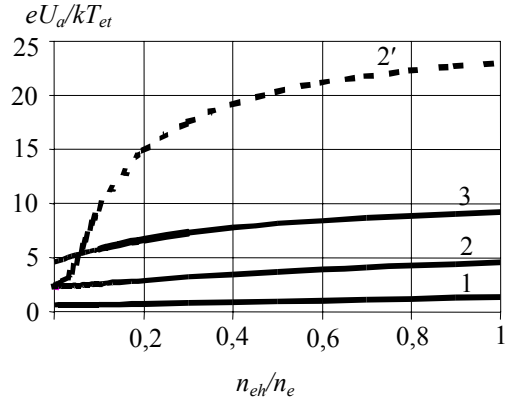


Fig. 1. Negative anode potential drop as a function of relative concentration of hot electrons. $n_{eb}$= 0; $T_{et}/T_{he}$ = 0,5 (1, 2, 3), 0,1 (2′); G = 2 (1), 10 (2, 2′), 100 (3)

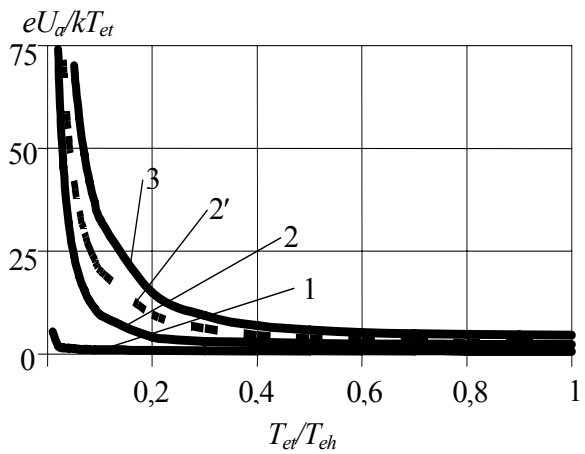


Fig. 2. Negative anode potential drop as a function of a thermal-hot electron temperature relation. $n_{eb}$=0; $n_{eh}/n_e$= 0,1 (1, 2, 3), 0,5 (2′); G = 2 (1), 10 (2, 2′), 100 (3)

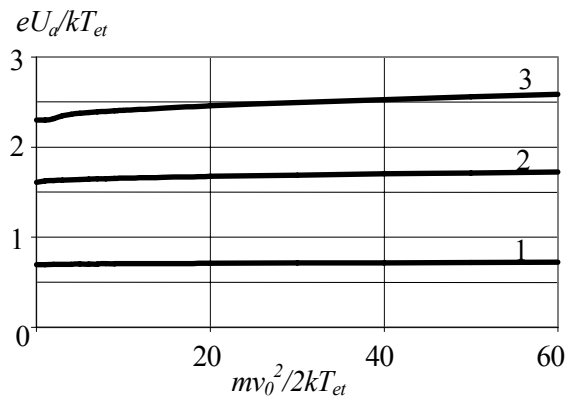


Fig. 3. Negative anode potential drop as a function of relative beam energy. $n_{eh}$=0; $T_{et}/T_{eb}$ = 10; $n_{eb}/n_e$= 0,001; G = 2 (1), 5 (2), 10 (3)

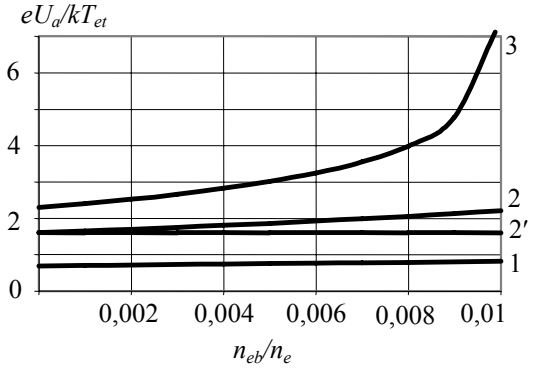


Fig. 4. Negative anode potential drop as a function of relative electron beam concentration. $n_{eh}$ = 0; $T_{et}/T_{eb}$= 10; $mv_0^2/(2kT_{et})$ = 10 (1, 2, 3), 1 (2′); G = 2 (1), 5 (2, 2′), 10 (3)

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