Comparative Parameters of Reflective Discharges with Two Types of Self-Heating Cathodes[1]

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Abstract – Parameters of two reflective discharge geometrics (a Penning discharge with a self-heated plate cathode and a combined discharge with an axial self-heated rod cathode) are compared. Parameters of self-sustained reflective discharges with self-heated cathodes in wide-ranging discharge cell geometrics and electron work functions are computed on base of the electron follow continuity equation and a power balance on the cathode. It is shown that considered systems differ essentially in a radial distribution of the fast electron density and electron currents.

1. Introduction

Discharge in crossed E×B fields is used as a source of charged [1–3] and neutral [4, 5] particles for a long time. An efficiency of cells based on such discharge can be raised without complication of its construction by including of a self-heated (hot) electrode [6, 7]. The electrode is heated up to noticeable temperature due to the energy evolved on the cathode during the discharge.

In spite of basic features of reflective discharge are known [1–3], a good theory allowing to calculate comprehensively discharge parameters including a current-voltage characteristic (CVC) does not still exist. Recently, an analytical model describing a correlation of ionization and recombination processes in the discharge has been formulated [8]. This model allows one to determine generally the necessary conditions of plasma discharge operation in crossed E×B fields. But results of [8] can't be directly applied because of the planar geometry to real discharge cells which usually have axially symmetric geometry.

CVCs of real reflective discharge cells can not be calculated by several reasons. Firstly, it is caused by difficulties with calculation of an ionization velocity and charged particles moving in crossed fields. Secondly, the discharge voltage is possible to estimate good enough within the linear model of gas ionization and charged particles drift but the discharge current can not be calculated without including of external circuit parameters in the model. Including of external circuit parameters makes the task very specific and does not allow one to analyze general features of a discharge system.

In [7] were shown that it is including of self-heated electrodes that allows to calculate real reflective discharge parameters with a satisfied accuracy. The present paper demonstrates that the model formulated in [7] allows one to calculate parameters of the discharge in crossed E×B fields even a geometry of a self-heated electrode will be changed. In this paper, two types of the electrodes are considered: in the first case the self-heated electrode is one of plate cathodes of the Penning cell and in the second case one is the additional axial rod cathode which transforms it to a cell with combined (magnetron-reflective) discharge.

2. Model and Main Equations

Discharge cells consisted of cylindrical anode *1* and two parallel plate cathodes *3* of a radius R spaced on the distance h are placed in a longitudinal magnetic field (see Fig. 1). One of the plate cathodes is supposed to be heat-insulated and can operate in thermal electron emission regime, another is cold. The combined discharge cell has the same geometry but both plate cathodes are cold and there is the self-heated heat-insulated axial rod electrode *2* of a radius R_0 being at the cathode potential.

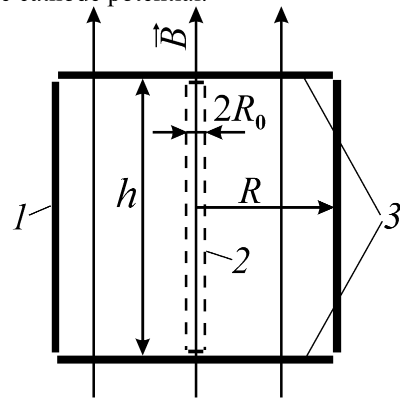

Fig. 1. Scheme of the discharge cells: *1* – cylindrical anode, *2* – axial self-heated electrode, *3* – plate cathodes

For the calculation of principal plasma parameters and CVCs of the discharge the following simplifying assumptions were made.

(i) The discharge was considered to operate in a high-current mode where the voltage drop was almost completely localized in the near-cathode layer. In this

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mode the main interelectrode space was filled by quasineutral plasma (discharge column) separated from the electrodes by narrow space charge layers whose dimensions were neglected. This assumption allows us to avoid the Poisson's equation for an anode layer.

(II) The column plasma was assumed to be low ionized. That limits the model application to not very low gas pressures.

(III) It was supposed that a flow of fast electrons whose energy approximately corresponds to the operating voltage was formed in the near-cathode layer. The electrons flow transfers the energy supplied by a power source to the discharge plasma and provides the gas ionization.

(IV) The gas ionization by comparatively slow (plasma) electrons of the plasma column was completely neglected. The role of the plasma electrons was reduced to carrying a part of electric current passing through the gas transverse to magnetic lines. This way is rightful if the operating voltage is much greater then the gas ionization potential [8].

(V) It was assumed that ions were not magnetized and the ion current was uniformly distributed over the all cathode area. Moreover, the nonuniformity of the plasma density along the height of the discharge cell wasn't taken into account. This height averaging simplifies the calculation significantly and allows us to analyze the discharge features more efficiently.

(VI) The self-heated cathode temperature was supposed to be uniform over the surface and controlled by the power balance of the energy-release due to an ion bombardment and a radiant heat removal (other energy removal channels are neglected).

Calculation of discharge parameters was made analogously to [7]. With the above assumptions, CVCs were computed in several steps: (I) calculation of the radial distribution of fast electrons; (II) calculation of the radial distribution of fast and slow electron currents; (III) formulation of the criterion of the self-sustained discharge and determination of the total ions current to cathodes; (IV) calculation of the hot cathode temperature and the thermionic current; (V) calculation of the secondary electrons current and the total discharge current.

The flux density of fast electrons jf transverse to magnetic lines has a diffusion mechanism and can be written as

$$j_f(r) = -D_f \frac{dn_f(r)}{dr}, \qquad (1)$$

where n_f is the fast electrons density, r is the radial coordinate, D_f is the average coefficient of a classical diffusion of fast electrons transverse to magnetic lines, which can be written approximately as

$$D_f \approx \frac{1}{3}\left\langle \frac{r_{Le}^2}{\tau_a} \right\rangle \approx \frac{4}{3}\frac{mU_c}{e\tau_i B^2}, \qquad (2)$$

where r_{Le} is Larmor radius of fast electrons, τ_a is the average time between collisions, τ_i is the average time of gas ionization (here $\tau_a = \tau_i/2$ is taken for the definiteness), U_c – the cathode potential drop, B – the magnetic flux density, m – the electron mass, e – the electron charge.

The continuity equation of the fast electrons flux density can be written in the form

$$\frac{1}{r}\frac{d(rj_f)}{dr} = \frac{j_{f0}}{h} - \frac{n_f}{\tau_f}, \qquad (3)$$

where j_{f0} is the initial flux density of fast electrons, $\tau_f = (eU_c/E_i)/\nu_i$ (where E_i is the average energy going into the formation of electron-ion pair and ν_i is the average ionization frequency by fast electrons) is the "lifetime" of fast electrons.

The stationary continuity equation of the slow electrons flux density is

$$\frac{1}{r}\frac{d(rj_s)}{dr} = \nu_i n_f = (\mu+1)\frac{n_f}{\tau_f}, \qquad (4)$$

where $\mu = eU_c/E_i$ is the secondary electrons multiplication factor by one fast electron.

Assuming the heat radiation goes away easy and the bombarding ions energy dissipates into the cathode completely, the hot cathode power balance can be written in the form

$$S_{h0}\varepsilon_T \sigma T_h^4 \approx eU_c J_{ic}\frac{S_h}{S_h + S_c}, \qquad (5)$$

where σ is the Stefan-Boltzmann constant, $\varepsilon_T \approx 0.5$ is the blackness coefficient, J_{ic} is the total ion current on the cathodes, S_{h0} is the area of the radiation hot cathode surface, S_h is the area of the emission hot cathode surface, S_c is the area of the cold cathode surface.

The hot cathode temperature T_h can be expressed from (5):

$$T_h^4 = \frac{eU_c J_{ic} S_h}{S_{h0}\varepsilon_T \sigma (S_h + S_c)}. \qquad (6)$$

The thermionic electron current is

$$J_{em} = S_h \cdot A_0\, T_h^2 \exp(-\varphi_h/kT_h). \qquad (7)$$

Here φ_h is the electron work function, $A_0 \approx 100$ A/cm$^2 \cdot$ K^2.

The set of eqs. (1)–(7) allows one to calculate T_h, J_{em}, and J_{ic} if the discharge cell geometry, the magnetic flux density, and the operating voltage are known. After that, the total discharge current J can be easy calculated:

$$J = J_{em} + (1+\gamma)J_{ic}, \qquad (8)$$

where γ is the ion-electron emission coefficient, J_{ic} can be determined from (5).

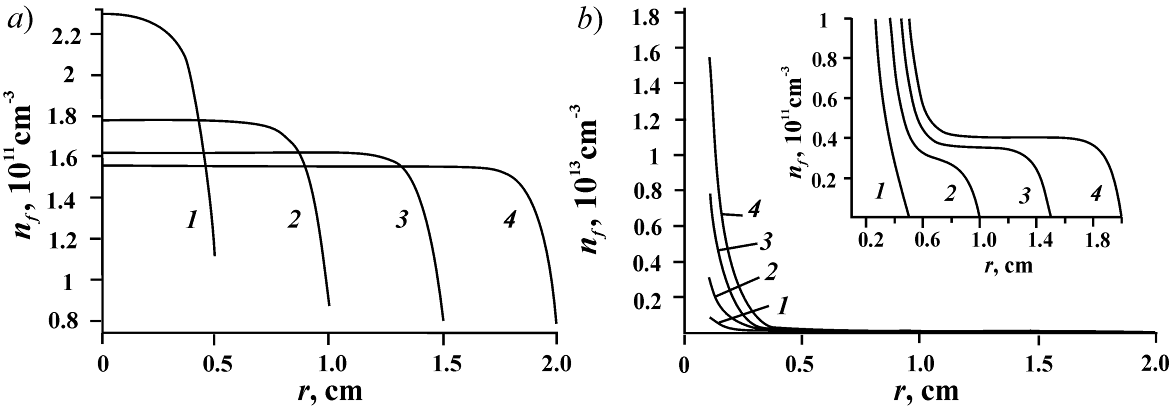

Fig. 2. Radial distributions of fast electrons concentration $n_f(r)$ in Penning (*a*) and combined (*b*) discharges with self-heated cathodes at different R (U_C = 150 V, p = 1 Torr, φ_h = 4.54 eV, γ = 0.05, B = 0.08 T, h = 1 cm, R_0 = 0.1 cm). *1* – R = 0.5 cm, *2* – R = 1 cm, *3* – R = 1.5 cm, *4* – R = 2 cm

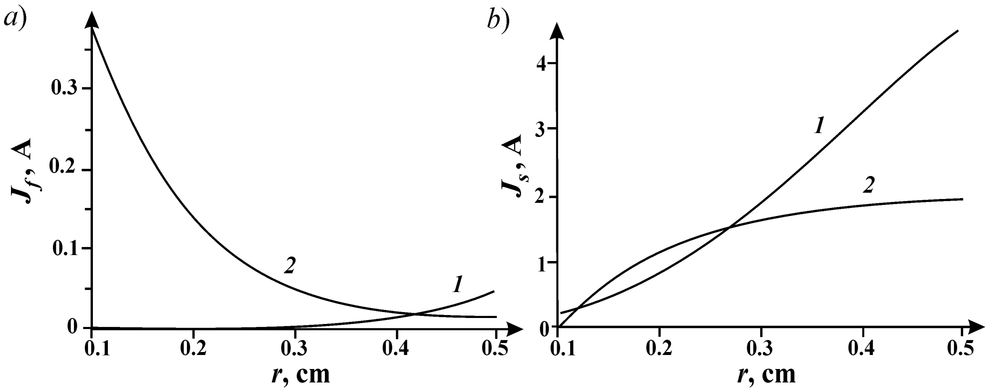

Fig. 3. Radial distributions of fast J_f (*a*) and slow J_S (*b*) electron currents in Penning (*1*) and combined (*2*) discharges with self-heated cathodes (U_C = 150 V, p = 1 Torr, φ_h = 4.54 eV, γ = 0.05, B = 0.08 T, h = 1 cm, R = 0.5 cm, R_0 = 0.1 cm)

Thereby, CVCs of the discharges and Th can be calculated within satisfaction accuracy. The model assumptions lead to an absence of the gas concentration in all equations, therefore, our calculations give the CVCs evidently independent from the gas pressure. This dependence can appear marginally if the relation between Ei and real ionization process kinetics will be taken into account.

3. Results and Discussion

Radial distributions of fast electrons $n_f(r)$ in the Penning discharge are shown in Fig. 2, *a*. The fast electrons density is constant over the almost all discharge region and reduces only near the anode at the same anode radius R. It is obvious that the shape of $n_f(r)$ is kept at changing of R. Raising of R results in decreasing of n_f, furthermore, the decreasing is more appreciable at small R. This is occurred because of T_h is reduced through changing a ratio of emission and radiation surfaces areas.

Radial distributions of fast electrons $n_f(r)$ in the combined discharge are shown in Fig. 2, *b*. The fast electrons concentration reduces sharply near the self-heated rod cathode at the same R. Moreover, the fast electron concentration is raised in a few times near the hot cathode in increasing the anode radius. It is deal with increasing of the temperature required for the discharge operation. In other discharge region, the profile of $n_f(r)$ is similar to the distribution calculated for the Penning discharge. But absolute magnitudes of the fast electron density are smaller because of plate cathodes of the combined cell are cold (see the insertion in Fig. 2, *b*). It is seen that the shape of $n_f(r)$ isn't kept at the different R.

The calculations show that the current is mainly transported by slow electrons (see Fig. 3).

Calculated current-voltage characteristics of discharges and corresponding temperatures are shown in Fig. 4. LaB$_6$ (φ_h = 2.8 eV), W (φ_h = 4.5 eV), and Re (φ_h = 5.0 eV) were chosen for comparison. Experimental CVCs of the combined discharge in hydrogen (the data for W-hot cathode were taken from [7]) are shown in Fig. 4, *b* too.

It is obvious that CVCs of studied discharges are dropping dependences of the current on the voltage which is characterized for arc discharges. The represented plots show that the operating voltage drops with reducing of the electron work function. The same results were obtained experimentally, for example, in [3].

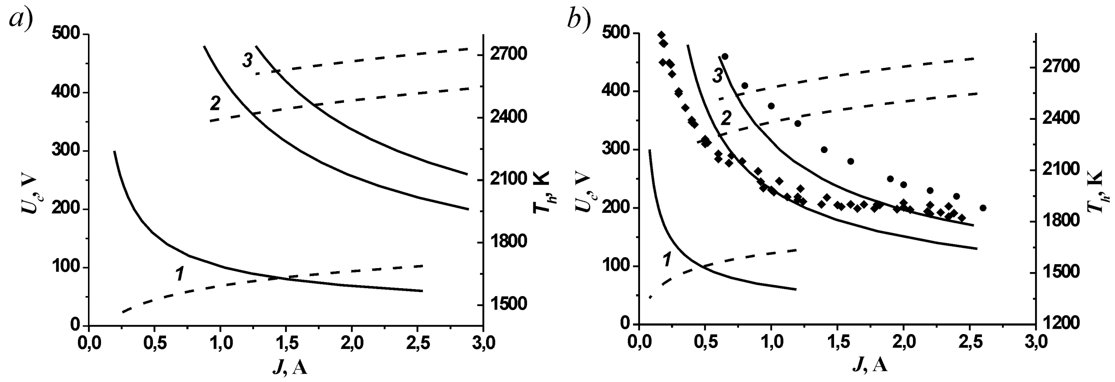

Fig. 4. Current-voltage characteristics (solid lines) of Penning (a) and combined (b) discharges with hot cathodes and corresponding temperatures of self-heated cathodes (dashed lines) at $B = 0.08$ T, $h = 1$ cm, $R = 0.5$ cm, $R_0 = 0.1$ cm. *1* – LaB_6; *2* – W, *3* – Re, ♦ – is the experimental current-voltage characteristic for W, • – is the experimental current-voltage characteristic for Re

The characteristics were computed at $E_i = 40$ eV and $\gamma = 0.12$ (LaB_6), $\gamma = 0.1$ (W), $\gamma = 0.09$ (Re). The calculated CVCs describe the experimental dependences qualitatively good. Some discrepancy theoretical and experimental characteristics, especially at high discharge currents, may be deal with unaccounted discharge and anode voltage droppings, and thermal effects.

Based on described features a discharge cell can be optimized. The Penning discharge cell can be used, for example, for extraction of uniform particle flows with large crossed section. The combined discharge cell can be used, for instance, for extraction of intense flows of neutral and charged particles from small axial hole.

4. Summary

The model described the ionization and recombination processes in the crossed E×B fields discharge allows one to calculate current-voltage characteristics of Penning and combined discharges at different sizes and electron work functions, the self-heated cathode temperatures, radial distributions of the fast electrons and currents in terms of the general method. So the model allows one to optimize the construction of neutral and charged particle sources based on such discharges.

It is shown that Penning and combined discharges are differ essentially in radial distributions of fast electrons and electron currents.

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