Computer Modeling of Characteristics of Heavy Current Radio-Frequency Argon Discharge

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Abstract — **Two theoretical experimental models, describing electric field and gas temperature of RF argon discharges are presented. Numerical simulations show a way to prevent the thermal overheating of the discharge by the variation of current density and electric field at a constant electric power. An increase of almost 100^0C of the maximum argon gas temperature with the 10-15% increase of the measureless electric power is also obtained.**

***Keywords* — RF (radio-frequency) discharge, electric field, gas temperature, overheating.**

I. INTRODUCTION

A subject of numerical study is the electrical field and the temperature profile of the neutral gas in RF capacity argon discharge. This type of discharge continues to be topical and is a subject of analytical and numerical studies. The RF discharges have a number of advantages: higher volumetric density of the electrical power, better ionizing stability. The externally fixed electrodes make the gas discharge device more reliable and with a bigger operating time. The RF discharge finds great use in a number of gas discharge devices: gas lasers and metal vapor lasers, in order to produce thin layers (thin films), in the semi-conductor industry (etching), for light sources and displays. They are used in analytical chemistry for spectral analysis of the solid materials.

Electric and temperature fields are the main characteristics of the gas discharge. They determine gas kinetic, electrical, thermal and optical characteristics of the discharge and are a subject of active studies. The values of these quantities depend on a huge amount of factors: geometric design, type and pressure of the inert gas, voltage and electricity in the discharge, type and quality of the materials, conditions for cooling the device. Numerical modeling often only allows evaluation of the huge amount of factors and as a result defines the most optimal characteristics and conditions for the use of the gas discharge device.

There is a large number of mathematical models, which allow the determination of the characteristics of the gas discharge device, including the electric field and the temperature profile. Detailed description of the existing models is given in [1-4] and the quoted literature there. In recent times there has been active work to create mixed (hybrid) models, which combine the advantages of the existing.

II. MODELING OF THE ELECTRIC FIELD

One of the hybrid models for determining the electric field is developed in [3]. This model is entirely theoretical and is based on two famous models - the fluid and the Monte-Carlo models. The purely theoretical models have some disadvantages: connected with the long calculation time, they calculate simple geometric lines and simple boundary conditions. Despite of the huge amount of examined equations they aren't precise enough. They are hard to use for calculating complicated optimizing problems.

The model we suggested is also hybrid – theoretical-experimental. A modified fluid model is used in the base by using experimental data: distribution of the charged particles inside the volume of the discharge, speed and ionized sections and constants. With this model a number of equations calculating the well known characteristics of the discharge are excluded. It is possible, that the electric field can be defined more precisely in complicated geometric design and allow the multidimensional optimizing problems in order to find the effective values of the electric field while solving specific engineering problems (see also [5]).

A. Description of the model

We will consider the heave-current discharge (γ discharge) inside an argon medium with a current of 30 *Torr*, a charging frequency of 13,56 *MHz* and electric power 200*W*. With this type of discharge the density of the current is considerable (up to 400 mA/cm^2). The physical law for the constant density of the current is broken and by increasing the voltage the current grows. A secondary electric emission from the electrons rises (γ processes). This type of discharge can be compared with the constant-current abnormal glow discharge. With these conditions the parameters of the plasma are defined in a time, considerably smaller than the half-period of the charging frequency. This means the conductivity current exceeds the displacement current and the conductivity of the plasma is coming close to that of the constant-current glow discharge: $\sigma = en_e v_d$, $\vec{j} = \sigma \vec{E}$. Here e is the electron charge, μ_e is the electron mobility, v_d is the drift velocity, $\vec{j}$ is the current density and $\vec{E}$ is the electric field distribution.

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As an example we will consider the geometric design of the discharge device, consisting of two inserted cylindrical tubes, the external made by quartz and the internal by Al_2O_3, and supplied with two external symmetric longitudinal electrodes (see Fig. 1). This kind of geometry is typical for some metal vapor lasers [6].

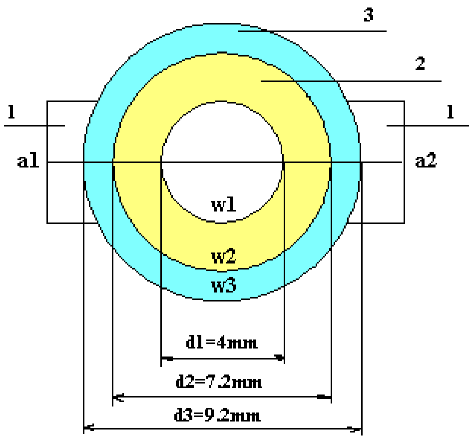

Fig. 1. Example of the cross-section of a discharge device: 1- external electrodes; 2- Al_2O_3 tube; 3- qwartzous tube

In order to obtain the scalar potential distribution in the cross section of the volume discharge we solve two-dimensional quasistationary Poisson equation

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}=-\frac{e}{\varepsilon_0}\left(n_i(x,y)-n_e(x,y)\right) \qquad (1)$$

under the following mixed boundary value conditions:

$$\varphi_L=0,\ \varphi_R=U_a, \qquad (2)$$

$$\varphi_\Gamma=0, \qquad (3)$$

$$\varepsilon_i E_{in}=\varepsilon_j E_{jn}, \qquad (4)$$

where ε_0 is the dielectric constant, $n_i(x,y)$ and $n_e(x,y)$ are the ion and electron concentrations, respectively. The boundary conditions (2) describe that at the left electrode the applied voltage is zero, and at the right electrode is U_a. The zero condition (3) represent the often grounded metal body of the discharge tube, i.e. zero potential (Dirichlet condition). The condition (4) take into account the electric field transfer trough the boundaries of the two dielectrics (Newmann condition), where E_{in} and E_{jn} denote the normal components of the electric field on the boundaries of the materials with dielectric constants ε_i, ε_j.

Fig.2 shows a typical experimental particle distribution in γ discharge [1]. Similar distributions are calculated in [3].

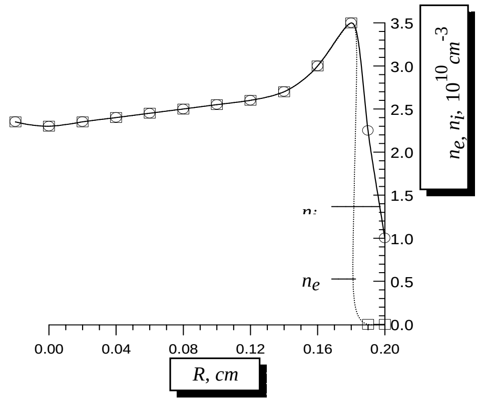

Fig. 2. Distribution of the charged particles n_e, n_i on the line $a1$-$a2$.

In order to determine the electric field we apply the following algorithm: (a) Begin to give the voltage U_a at the right (charged) electrode and typical distributions of the charged particles (for our example see Fig.2); (b) Find the potential U by solving the problem (1-4); (3) Calculate the electric field from $\vec{E}=-\mathrm{grad}\,U$; (d) Find the current density by means of the formula $j=en_e v_d E$ with $v_d=f(E/p)$ for the argon [7]; (e) Calculate the volume average density of the electric power $\langle jE\rangle$ and the total power $P=\langle jE\rangle V$, where V is the volume of the discharge; (f) If the resulting power P differs to the initial power P_0, than change the data for $n_i(x,y)$ and $n_e(x,y)$ and repeat the calculations until $P=P_0$ is reached.

B. Numerical results and discussion

The model was carried out for an initial power P_0=200W and different electrode voltage U_a, applied to the charged electrode. The solution of the elliptic problem (1)-(4) was obtained by means of a finite difference scheme of accuracy order $O(h^2)$, with step $h\to 0$ and the successive over-relaxation method (SOR method).Fig. 3 shows the scalar potential distributions and electric field intensity E on the central line $a1$-$a2$ (see Fig.1) at U_a =200V. Fig. 4 illustrates the electric field distributions at U_a =200V and 400V, respectively. These numerical results are in good qualitative agreements with simple one-dimensional analytical models [1] and discharges, operating at similar conditions [8]. The availability of higher values of the electric field E at the electrode region can be explained by the noncompensate electron charges in this region.

The model allows to evaluate the variation of current density j and electric field E at the maintenance of a constant electric power P_0. Their values are of great importance for the outcome characteristics of the discharge device (for instant for the metal vapor laser devices it means the outcome laser power). The constant electric power P_0 provides a constant maximum temperature of the argon discharge, which prevent its thermal overheating.

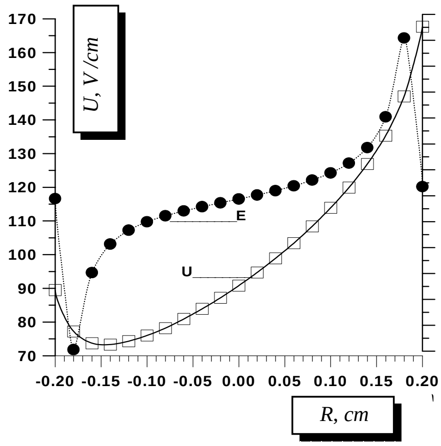

Fig. 3. Distributions of the potential U and electric field E on the central line $a1$-$a2$ at U_a =200V.

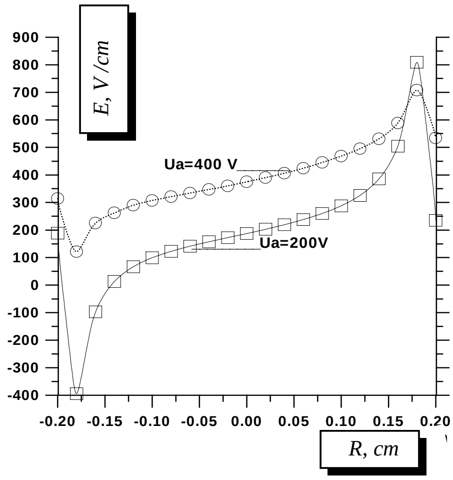

Fig. 4. Electric field distributions at U_a =200V and 400V on the line $a1$-$a2$ at a constant electric power P_0 = 200W.

III. MODELING OF THE GAS TEMPERATURE PROFILE

The overheating of the argon gas medium could considerably influence the discharge parameters and even to make device unusable. For this reason, the gas temperature T_g is a subject of permanent interest [4]. In [4] a complex theoretical hybrid method, including Monte-Carlo model, fluid method and heat conductivity equation for direct current argon discharge is developed.

In our considerations for heavy current argon discharge a theoretical experimental approach is applied. It is based on the solution of two-dimensional steady state heat conductivity equation and the results from the previous section, under the same assumptions. In addition the known experimental data for the heat conductivity coefficient, kinematical viscosity coefficient, the volume extension coefficients of the materials and gases are used.

A. Description of the mathematical model

Only a brief description of the model will be presented here. More detailed similar model was developed in [9-10]. In order to find the temperature of the neutral argon gas T_g in the cross section of the discharge it is necessary to solve the two-dimensional steady state heat conductivity equation

$$\operatorname{div}(\lambda_g \operatorname{grad} T_g) + q_v = 0, \tag{5}$$

where λ_g is the conductivity coefficient of the argon gas, q_v is an internal temperature source. The Eq. 5 was solved with the mixed boundary value conditions of the third and fourth kind in cylindrical configuration [11]

$$Q = \alpha F_{w3}(T_{w3} - T_f) + F_{w3}\varepsilon c[(T_{w3} / 100)^4 - (T_f / 100)^4], \tag{6}$$

$$q_l = 2\pi\lambda_1(T_{w1} - T_{w2}) / \ln(d_2 - d_1), \tag{7}$$

$$q_l = 2\pi\lambda_2 (T_{w2} - T_{w3}) / \ln(d_3 - d_2), \tag{8}$$

where Q is the total heat flux, T_{w1}, T_{w2} and T_{w3} are the temperatures of the three surfaces $w1$, $w2$ and $w3$, respectively (see Fig.1), T_f is the surroundings temperature, λ_1 and λ_2 are the thermal conductivities of the internal and external mediums, α is the heat transfer coefficient, ε is integral emisivity of the material, c = 5,67 $W/(m^2K^4)$ is the black body radiation coefficient, F_{w3} is the outside surface area, $q_l = Q/l$ is the linear density of the heat flux and l is the length of the discharge tube. Eq. 6 shows the heat exchange through the surroundings and the outer surface of the body. The first term at the right hand side represents the Newton-Rihmann's law of convective heat exchange and the second term represents the Stefan-Boltzmann law of radiation heat exchange. The Eqs. 7-8 give the heat transfer condition trough the two contacting surfaces of the composite wall in cylindrical configuration.

The function q_v is found by using the results from the previous section and the formula $q_v(x,y) = j(x,y)E(x,y)$. The heat transfer coefficient α is calculated by means of the Nusselt criteria $Nu = \alpha H / \lambda$ [11]. For a free convection the Grashof criteria is given by $Gr = g\beta H^3 \Delta T / \upsilon^2$, where g is the gravitational acceleration, β is the coefficient of cubical heat expansion of the gas, $\Delta T = T_{w3} - T_f$ is the temperature difference of the wall and the fluid and ν is its kinetic viscosity. For the horizontal tubes at natural air convection the following dependence holds $Nu = 0{,}46\, Gr^{0,25}$ [11].

In the calculations we use T_f = 300K, $H = d_3$ = 9,2mm, β_{air} =3,41.10$^{-3}K^{-1}$, λ_{air} = 0,0251$W(mK)$, υ_{air} = 15,7.10$^{-6}m^2/s$ [7].

B. Numerical results and discussion

For numerical solving of the Eqs. 5-8 we applied finite difference method. The conditions (7)-(8) were radially transferred to the external boundary (see [9-10]).

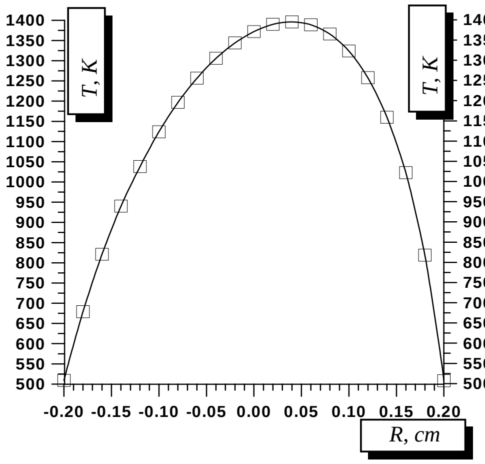

Fig. 5. The temperature distribution T_g on the line $a1$-$a2$.

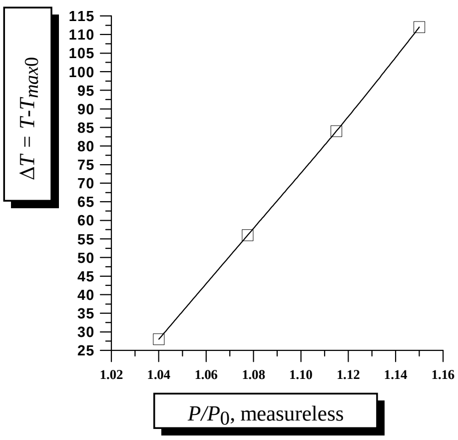

Fig. 6. Absolute increase of the maximum temperature $\Delta T = T - T_{max0}$ with respect of a of the electric power P/P_0.

Fig. 5 illustrates the obtained gas temperature distribution T_g in the cross section of the discharge on the line $a1$-$a2$. The maximum temperature is not in the center and is a little shifted to the direction of the charged electrode. The latest fact is due to the asymmetrical power volume density distribution q_v, as well to the electric field E (see Fig.4).

The numerical determination of the temperature profile could be used for improving the engineering design and operational capacities of the discharge devices. In Fig. 6 the maximum argon gas temperature as a function of the electric power is drawn. It is shown an increase of the electric power with 10-15% involving the increase of the argon gas temperature by at almost 100^0C. It means, that a such increase of the power can cause bad operational parameters of the discharge and its physical destroy.

IV. CONCLUSION

The presented models can be also applied to other gas discharge devices, operating at the similar types of gas discharge. By numerical simulations the temperature profile can be optimized by different engineering solutions, including the cooling conditions, such as natural and constrained cooling, external metal fins, etc. The aim is to establish some optimal correlation between the electric power and the gas temperature in order to prevent the discharge overheating and to improve the outcome characteristics of the discharge.

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