Numerical model of a hollow cathode arc discharge formation in vacuum

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Abstract. Industrial application of hollow cathode arc (HCA) discharge necessitates understanding the processes of interaction between the plasma and the cathode and the anode, as well as related processes. The first step is to study the formation process of HCA discharge in vacuum with the micro-flow of plasma-forming gas through the hollow cathode. In this work presents a two-dimensional model describing the related processes of transfer of charged particles and the movement of plasma-forming gas flows. Electron density and mean electron energy are calculated by solving the drift-diffusion equations. The mass transfer equation for a multicomponent mixture is used to describe the mass transfer of heavy plasma particles. To calculate the electric field strength the Poisson equation is used. The emission of secondary electrons from the inner surface of the cathode is taken into account. The boundary conditions take into account the loss of charge as a result of chaotic motion and its occurrence due to thermal emission effects. The gas flow is determined by collisions and diffuse re-reflection from all surfaces assumed in accordance with Knudsen's law. Calculations of plasma formation and the movement of plasma-forming gas flows were performed using the simulation package COMSOL Multiphysics.

1. Introduction

One of the most common sources of energy for welding, surfacing and related technology is electric arc discharge. The combination of the efficiency of vacuum protection and the properties of the electric arc as an energy source for creating arc welding processes in vacuum on their basis seems very promising. This technical problem served as the basis for the development of arc welding processes in vacuum. As a result a scheme was chosen for producing an arc discharge with a non-consumable thermionic hollow cathode in vacuum, the main advantage of which is the possibility of obtaining, under certain conditions, a low value of specific erosion.

Industrial application of hollow cathode arc (HCA) discharge necessitates understanding the processes of interaction between the plasma and the cathode and the anode, as well as related processes. The theory acquires a particularly important role in the development of new arc processes under specific...
conditions different from traditional ones, since in these cases the experiment alone often does not make it possible to carry out the required process. The first step is to study the formation process of HCA discharge in vacuum with the micro-flow of plasma-forming gas through the hollow cathode. When studying arc discharges in vacuum, the fundamental work of physicists involved in the theory of gas discharges was used [1-4].

2. Mathematical model
In this work presents a 2D model to investigate the HCA discharge in vacuum when argon used as the plasma-forming gas. The calculations of plasma formation and the movement of plasma-forming gas flows were performed using the simulation package COMSOL Multiphysics.

Figure 1 shows a scheme of the model (calculations are performed in cylindrical coordinates in an axisymmetric formulation). Hollow cathode parameters: inner radius \( r_c = 1.5 \text{ mm} \), cathode thickness \( \delta_c = 1 \text{ mm} \), length \( l_c = 10 \text{ mm} \).

![Figure 1. Schematic of the HCA discharge model: 1 – axis of symmetry, 2 – anode \((U=0)\), 3 and 6 – gas outlet \((S=100 \text{ [l/s]}\)), 4 – cathode \((U=U_0)\), 5 – gas inlet \((Q_m)\).](image)

3. Governing equations
Electron density and mean electron energy are calculated by solving the drift-diffusion equations [1, 5, 6]:

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{G}_e + (\mathbf{u}_g \cdot \nabla) n_e = R_e
\]

\[
\frac{\partial n \varepsilon}{\partial t} + \nabla \cdot \mathbf{G} \varepsilon + \mathbf{G}_e \cdot \mathbf{E} + (\mathbf{u}_g \cdot \nabla) n \varepsilon = R \varepsilon
\]

where \( n_e \) and \( \varepsilon \) are the electron density and electron energy density, respectively. \( \mathbf{G}_e \) and \( \mathbf{G}_\varepsilon \) are the electron flux and electron energy flux. The collision source term \( R_e \) represents the production or loss of electrons, and the electron impact reactions are summarized in Table 1 [7-9]. In these equations, \( R_e \) represents the electron energy change in those reactions, \( \mathbf{u}_g \) is the flow velocity of neutral gas, and \( \mathbf{E} \) is the electric field intensity.
Table 1. Plasma chemistry reactions.

| №  | Formula                        | Data of reaction | Type of interaction |
|----|--------------------------------|------------------|--------------------|
| 1  | $e + Ar \rightarrow Ar + e$   | cross-section    | elastic            |
| 2  | $e + Ar \rightarrow Ar^* + e$ | cross-section    | excitation         |
| 3  | $e + Ar^* \rightarrow Ar + e$ | cross-section    | excitation         |
| 4  | $e + Ar^* \rightarrow Ar^* + 2e$ | cross-section    | ionization         |
| 5  | $e + Ar \rightarrow Ar^* + 2e$ | cross-section    | ionization         |

The mass transfer equation for a multicomponent mixture is used to describe the mass transfer of heavy plasma particles [10–12]:

$$\rho \frac{\partial \omega_k}{\partial t} + \rho (u_g \cdot \nabla) \omega_k + \nabla \cdot G_k = R_k$$  \hspace{1cm} (3)

where $\rho$ is the mass density of the working gas, $\omega_k$ is the mass fraction of the $k$th species, $R_k$ is a collision term of the heavy particles, derived from the plasma chemical kinetic reactions in Table 1, $G_k$ is the flux of the $k$th species.

To calculate the electric field intensity, the Poisson’s equation is used:

$$-\varepsilon_0 \nabla \cdot (\nabla U) = \varepsilon_0 \nabla \cdot E = \rho$$  \hspace{1cm} (4)

where $U$ is the electrostatic potential of plasma, $\rho$ is the volume density of the charge, and $\varepsilon_0$ is the dielectric constant of vacuum.

Discharge in plasma is accompanied by the emission of secondary electrons from the surface of cathode. The boundary conditions take into account the loss of charge as a result of chaotic motion and its occurrence due to thermal emission effects [11]:

$$-n \cdot G_e = \left( \frac{1}{2v_{e,t} n_e} \right) + n_e \mu_e E \cdot n - n \cdot G_t$$  \hspace{1cm} (5)

and for the electrons energy flux:

$$-n \cdot G = \left( \frac{1}{2v_{e,t} n_e} \right) + n_e \mu_e E \cdot n$$  \hspace{1cm} (6)

where $v_{e,t}$ is the thermal velocity of electrons, $G_t = J_e/e$ is the thermal electron emission flux and $n$ is the surface normal, $\mu_e$ and $\mu_e$ are electron mobility and electron energy diffusion coefficients.

Boundary condition for electron flux, electron energy flux and heavy particle flux on edges 2, 3, 4, 5, 6 detailed in [13].

The gas flow is determined by collisions and diffuse re-reflection from all surfaces assumed in accordance with Knudsen's law using Free Molecular Flow module of COMSOL Multiphysics.

4. Results

Figure 2 shows the calculated electron density distribution during HCA discharge in vacuum with the micro-flow of plasma-forming gas (Argon) through the hollow cathode cavity. Preliminary calculations have shown that the maximum of electron density is located near the hollow cathode tip.
Figure 2. Electron density distribution during HCA discharge (discharge current $I_d = 96$A, electric potential $U_0 = 30$ V, gas flow $Q_m = 3$ mg/s).

5. Conclusion
This work presents a model of the HCA discharge describing the related processes of plasma formation, transfer of charged particles and the distribution of plasma-forming gas.

Qualitatively, the results do not contradict the known theoretical calculations and experiments. At further research should to take into account heat and mass transfer in the process of forming an HCA discharge and study this question in detail also for use of the developed model, it is necessary to calibrate it and perform verification based on experimental data.

6. Acknowledgments
The reported study was supported by the Government of Perm Krai research project Nr. S-26/795 of December 21, 2017, by the grant from the Russian Foundation for Basic Research RFBR Nr. 18-08-01016 A, as well as by Ministry of Science and Higher Education at the base part of the state assignment Nr. 9.9697.2017/8.9.

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