Effect of the mesh emission electrode shape on the distribution of the plasma density generated in the working chamber

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Abstract. The research of the influence of the shape of emission mesh electrode on the distribution of the plasma density generated in the hollow cathode of low-pressure glow discharge was implemented. Radial and azimuthal distributions of the ion current density to the probe were measured for six shapes of the mesh emission electrode. For each shape of the emission electrode the non-uniformity factor of the ion current density distribution was calculated. These studies allow to optimize the electrode system to generate a high uniformity plasma (±25%).

1. Introduction
In low-pressure discharge generation systems, there is a problem of the plasma distribution uniformity in the working chamber. Plasma density distribution directly influence on the results of the product treatment. It’s necessary to take into account this fact since in industrial applications it is not always possible to rotate the products with large weight and complex geometry in the discharge volume [1]. The electrode system of a non-self-sustained low-pressure glow discharge with a large hollow cathode allows to independently regulate the operating pressure, discharge voltage and glow discharge current [2]. However, to treat large-sized products with complex geometry without rotating it is necessary to generate plasma with high uniformity (±25%). The mesh shape of emission electrode through which electrons are injected in the glow discharge hollow cathode can significantly change a pattern of the plasma density distribution. In this paper the influence of different shapes of the mesh emission electrode on the plasma density distribution was investigated.

2. Material and Methods
The influence of the mesh emission electrode shape on the plasma density distribution in the working chamber was investigated on a experimental bench (figure 1), based on the NNV 6.6-I1 installation. In this system the walls of the vacuum chamber with dimensions of 600×600×600 mm were the hollow cathode of the glow (main) discharge. The chamber was pumped out by a turbomolecular pump to a residual pressure of 5·10^{-3} Pa. The working gas pressure was varied in the range of (0.4-2) Pa. The non-self-sustained glow discharge was ignited between the hollow cathode 1 with an area $S_c=2.3\times10^4$ cm$^2$, and the plane anode 2,fig with an area $S_a=500$ cm$^2$. The glow discharge was supplied by a pulse voltage source with the following parameters: output voltage $U_d=(30-300)$ V, pulsed current $I_d=(1-500)$ A with a maximum average output current $I_{d,av}=120$ A, maximum average power
$P=30 \text{ kW}$, the output voltage instability is ±5%, pulse repetition frequency $f=(1-1000) \text{ Hz}$, the pulse duty factor $\gamma=(1-100) \%$. To reduce the voltage drop during the discharge pulse time, the 7.2 mF capacitor bank was installed at the output of the discharge power supply.

Figure 1. Schematic of the experimental bench: 1 – cathode of glow discharge; 2 – anode of a glow discharge; 3 – magnetic coil; 4 – gas inlet; 5 – igniting electrode; 6 – hollow cathode of auxiliary arc discharge; 7 – arc quencher; 8 – conical mesh anode of auxiliary arc discharge; 9 – cylindrical Langmuir probe; 10 – grid; 11 – plane probe with a guard ring.

The amplitude of the discharge current was measured by the Hall sensor and the discharge voltage was measured with an 1:100 oscilloscope probe between the anode and the cathode. For stable ignition and burning of the main glow discharge, it was used an electron source based on the arc discharge with an integrally cold hollow cathode. When nitrogen is being supplied through the gas inlet 4 and a high voltage pulse is being fed between the igniter electrode 5 and the hollow cylindrical cathode 6, the arc discharge initiates. The cathode spot moves along the inner surface of the cylindrical hollow cathode 6 at the maximum of the tangential component of the axial magnetic field produced by the coil 3 [3]. This steady-state auxiliary arc discharge operated between hollow cathode 6 and conical mesh anode through the aperture of the arc quencher 7, which under the “floating” potential prevents “escaping” of the cathode spot to the edge as well as the transition of the arc from the diffuse burning mode in the anode region to the contraction mode with the formation of an anode spot on the nearby section of the anode [4]. The anode of the auxiliary discharge 8, which is under the potential of the hollow cathode of a glow discharge was an axially symmetric emission electrode covered by a fine-grained mesh with geometric transparency of 65% (mesh cell size is 0.4×0.4 mm). During the experiments, electrodes of six different shapes were used (figure 2). To determine the character of the azimuthal distribution of the ion current density, we used a plane probe 11 with a diameter of 5 mm with a guard ring having the potential of a hollow cathode of a glow discharge, and to determine the radial distribution – a single cylindrical Langmuir probe 9. To measure the azimuthal distribution of the ion current density, the probe was rotated around the center of the chamber at a distance of 18 cm from the axis of the chamber and was placed at the axis height of the auxiliary plasma source, which was emitting the electrons. The probe was fixed in a flange at the bottom of the chamber and rotated to the angle $(0\div360) ^\circ$. It is necessary to say that in this type of glow discharge the electron temperature is $\approx1$ eV and little changes in hollow cathode volume [5] so considering this according to Bohm equation plasma density is linearly connected and will repeat the character of ion current density distributions.
Figure 2. Shapes of the mesh emission electrode: 1 – flattened cone with a concave central part; 2 – plane; 3 – cone; 4 – flattened cone with reduced transparency in the central part; 5 – flattened cone; 6 – flattened cone with the nontransparent central part.

The electron source based on the arc discharge with an integrally cold hollow cathode was supplied from an ARC150 stabilized current source providing a constant arc current to $I_a=150$ A at operating voltage up to $U_a=60$ V. Magnetic field $B$ induction on the axis of the electron source created by the magnetic coil 4 in all experiments was taken as $B=3.8$ mT. The azimuthal and radial distributions of the ion current density were measured in the pulsed combustion mode of the main non-self-sustained glow discharge with the following parameters: repetition frequency $f=38$ Hz and pulse duration $t_i=3.4$ ms ($\gamma=13\%$). The current and voltage values were determined at 3 ms from the beginning of the discharge pulse. Time-phased waveforms of the voltage and the current of the main glow discharge under the auxiliary discharge current $I_a=150$ A and the operating gas pressure $p(N_2)=1$ Pa are shown in figure 3.

Figure 3. Time-phased waveforms of current and voltage pulses for non-self-sustained glow discharge.

The waveform of the current is characterized by a long rise caused by the high value of the power source inductance. After the current reaches a maximum value of about 340 A, the voltage abruptly remove from main discharge gap, and current decreases with a small speed, $\sim 3$ A/$\mu$s. The discharge in the interval of time, starting from the time point of 1.8 ms and until the end of the pulse, burned in a quasi-stationary mode. Therefore, the time point of probe measurements was third millisecond from the beginning of the discharge pulse.
3. Results and Discussion
The shape of the mesh emission electrode directly influence on the distribution of the plasma density, because the initial direction of the injected electrons is perpendicular to the mesh surface. To compare the results of this influence the non-uniformity factor $k$ was introduced, which is equal to the ratio of the maximum deviation of the ion-current density from the mean value of the ion current to this average value, i.e.,

$$k = \frac{|j_n - j_{av}|_{\text{max}}}{j_{av}} \times 100\%$$

where, $j_n$ – ion current density at $n$ – turn angle of the probe with a guard ring, $j_{av}$ – arithmetic mean value of the ion current density. Azimuthal distributions of ion saturation current density to the plain probe measured at $p(N_2)=0.65$ Pa, $I_d=90$ A, $U_d=182$ V for different shapes of the grid anode are shown at figure 4.

![Azimuthal distributions of ion saturation current density to plain probe for different shapes of mesh emission electrode](image)

**Figure 4.** Azimuthal distributions of ion saturation current density to plain probe for different shapes of mesh emission electrode: 1 – flattened cone with a concave central part; 2 – plane; 3 – cone; 4 – flattened cone with reduced transparency in the central part; 5 – flattened cone; 6 – flattened cone with the nontransparent central part.

The most prominent maxima are observed for the plane shape of mesh emission electrode. The other distributions are approximately identical to each other. The radial distributions of the ion saturation current density to cylindrical probe shown in figure 5. For a plane shape and shapes with a flattened cone with reduced transparency of the central part, prominent maxima are observed in the center of the chamber.

The shape of the azimuthal distribution of the ion current density for the plane emission electrode (No. 1 in table 1) is likely to be caused by the fact that the injected electrons form a local maximum of the plasma density on the axis of the electron source. The calculated value of the electron mean free path at a pressure of 1 Pa is $\lambda=1/n_0\sigma \approx 28$cm, where $n_0$ is the density of neutrals ($2.4\times10^{20}$ m$^{-3}$) and $\sigma$ is the cross section for nitrogen ionization ($1.5\times10^{-20}$ m$^2$). Indeed the maximum plasma density is under the angle of 180° and the point of probe placement is just a little further than the electron mean free path. Besides maximum under the angle of 180° is due to the rectilinear trajectory of the electrons, which being in the electrostatic trap (the hollow cathode) reflect from the chamber wall in the cathode sheath, creating the highest number of ionization events in the given radius of the probe rotation.
Figure 5. Radial distributions of the of ion saturation current density to cylindrical probe at $p(N_2)=0.65$ Pa, $I_d=90$ A, $U_d=182$ V for different shapes of the mesh emission electrode.

The conical shape which chaotizes the electron flow significantly changes the distribution of the plasma density in the working chamber. It explains the similarity of the character of the azimuthal distributions for other shapes of the mesh emission electrode. Besides azimuthal distributions it’s necessary to analyze of the radial distributions of the ion current density for different emission electrode shapes.

Table 1 shows the values of auxiliary discharge currents for various mesh electrode configurations, as well as the values of the non-uniformity factor for radial and azimuthal distributions. The local maximum of the radial distribution for electrode No. 5 is conditioned by the fact that the upper part of the grid electrode is covered by a mesh located perpendicularly to the axis of the electron source, which means that the electron flux leaving the diaphragm of the arc quencher is practically not chaotized. The distributions obtained for electrodes No. 2, No. 4 and No. 6 are the most uniform, but if we compare the currents of the auxiliary arc discharge for these electrodes, the greatest value is reached by the electrode No. 6.

Table 1. The values of arc discharge current and nonuniformity factor for various mesh electrode configurations.

| № of shape | Auxiliary discharge current $I_a$, A | Non-uniformity factor for azimuthal distribution $k$, % | Non-uniformity factor for radial distribution $k$, % |
|------------|--------------------------------------|------------------------------------------------------|--------------------------------------------------|
| 1          | 32                                   | 32                                                   | 40                                               |
| 2          | 34                                   | 43                                                   | 26                                               |
| 3          | 39                                   | 55                                                   | 24                                               |
| 4          | 32                                   | 46                                                   | 24                                               |
| 5          | 35                                   | 49                                                   | 44                                               |
| 6          | 43                                   | 48                                                   | 24                                               |

For electrodes No. 2 and No. 4, the azimuthal and radial distributions obtained are the most similar. However if compared to the electrode No. 4, the electrode No. 2 leads to the significant loss of useful volume of vacuum chamber which should use for treated products.
4. Conclusion
According to determined values of the non-uniformity factor for the azimuthal and radial distributions and requirement to have the maximum useful volume for treated products the most promising shape of the mesh emission electrode is the flattened cone with a concave central part (Shape No. 4).

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