Ring shaped plasma structures in radio-frequency discharge between liquid jet electrodes

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Abstract. The effect of ring or semi-ring shaped plasma structures around the jet liquid electrodes in radio-frequency discharge is discussed. These structures occur owing to amplification of electric fields in jet constriction.

1. Introduction
Currently, plasma with liquid electrodes is widely used for a variety of ends [1]. The possibility of DC glow discharge purification of industrial wastewater from heavy metal ions are shown in [2]. Reducing the concentration of harmful organic impurities in water by discharges with a strong disequilibrium are discussed in [3].

Applications of discharges with liquid electrodes are being investigated for the treatment of parts manufactured by additive technology [4], optical materials [5], products of complex geometric shape [6], in ecology, and environmental protection [7].

Studies of discharges with liquid electrodes began at the end of the 19th century [8], continued in the twentieth century [1, 9-14]. The most studied at present are discharges with liquid DC electrodes [1]. Experimental studies of discharges with liquid electrodes generated by a rf current began recently [15-18]. The effect of annular or semiring-shaped structures occurred around the jet in some experiments with rf liquid jet electrodes [16] as can be seen from figure 1.

The aim of this work is to construct a possible mechanism for the occurrence these structures.

2. Setting the problem
The theory of RF discharge with liquid electrodes is off till now due to the complexity of the processes in the discharge. A mathematical model of the discharge should consider the interaction between three media: a fluid in a jet and an electrolytic bath, plasma-vapor discharge, and the surrounding neutral gas, taking into consideration free boundaries between the media, a liquid-vapor phase transition, and plasma-chemical reactions between electrolyte components evaporated into the plasma.

The complexity of the problem of modeling discharges with liquid electrodes is evidenced by the fact that up to 53 charged and neutral components in the plasma of moist air which act in more than 600 plasma-chemical reactions [19], 77 different plasma particles in dc discharge burned between two streams of tap water in open air is considered in [20], 41 plasma particles, including 10 particles transferred from the NaCl electrolyte cathode in a glow discharge is analyzed in [21].
Figure 1. Different forms of ringed structures near an electrolyte jet in RF discharge between liquid electrodes of saturated iodized NaCl solution in tap water at pressure $p = 10^5$ Pa, diameter of charge pipe 5 mm and jet length 3 mm. Labeling on the right-hand snapshot: 1 – electrolyte jet; 2 – electrolytic bath; 3 – half-ring shaped structure, 4 – charge pipe; 5 – discharge zone.

Let us consider the electromagnetic field influence on the environment surrounding the electrolyte stream. It is known that the electric field in capacitive coupled RF discharge contains an electrostatic part produced due to current rectification in the positive charge layer [22]. In accordance with the principle of superposition, we can separate the electrostatic $\mathbf{E}$ and the dyadodynamic $(\mathbf{E}, \mathbf{H})$ parts of the electromagnetic field. The current carriers are ions in the fluid, and electrons and ions in the plasma. The radio-frequency component of the electric field does not affect the ions motion; they drift in the average (electrostatic) field produced by the electrodes and positive charge layers. The electrostatic part of the electromagnetic field is found by means of the potential gradient $\mathbf{E} = -\nabla \varphi$. The electric potential $\varphi$, respectively, can be determined by solving the Poisson equation

$$\Delta \varphi = \frac{e}{\varepsilon \varepsilon_0} \sum Z_i^\pm n_i^\pm, \text{при } \mathbf{r} \in \Omega, \quad (1)$$

where $\Omega$ is the discharge region, $\mathbf{r}$ is radius vector, $e$ is the electron charge, $\varepsilon$ is the relative permittivity, $\varepsilon_0$ is the electric constant, $n_i^\pm$ is the positive and negative ions density, $Z_i^\pm$ is ionization multiplicity.

The dyadodynamic part of the electromagnetic field produced by jet current is determined by Maxwell’s equations

$$\nabla \times \mathbf{H} = \mathbf{j}, \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\nabla \cdot \mathbf{B} = 0, \quad \nabla \cdot \mathbf{D} = 0, \quad (2)$$

with the material relations $\mathbf{B} = \mu_0 \mu \mathbf{H}$, $\mathbf{D} = \varepsilon_0 \varepsilon \mathbf{E}$. Here $\mathbf{B}$, $\mathbf{H}$ are the vectors of magnetic induction and intensity, $\mathbf{D}$, $\mathbf{E}$ are electrical induction and intensity, $\mathbf{j}$ is the current density, $\mu_0$ is the permeability of vacuum, $\mu$ is specific media permeability, $\varepsilon_0$ is the electric constant, $\varepsilon$ is relative electric permittivity. Note that since the electromagnetic field extends indefinitely throughout space, equations (1), (2) in general should be considered in both the jet and non-flowing electrodes, as well as in the plasma and the surrounding air fields.

3. The approximate solution

Suppose the electrolyte stream the has the cylindrical symmetry. Let us consider a simplified model of a jet as a truncated cone coupled with a sine curve profile (figure 2). The radius of the base of the cone is 2.5 mm, the maximum radius of the sinusoid at the end of the considered section is 2 mm, the cone conjugates with the sine curve profile at a distance $z = 5$ mm from the base of the cone, the sinusoid
period is 5 mm, the sine curve amplitude is 1 mm. This scheme approximates the jet electrode profile observed in experiments [17].

The method of complex amplitudes is usually used to calculate radio-frequency fields, in which the vectors \( \vec{j}, \vec{H}, \) and \( \vec{E} \) are represented as
\[
\vec{j} = j_a \exp(i\omega t), \quad \vec{H} = H_a \exp(i\omega t), \quad \vec{E} = E_a \exp(i\omega t),
\]
where \( j_a, H_a, E_a \) are vectorial amplitudes, \( \omega = 2\pi f \) is cyclic frequency, \( f \) is current frequency, \( i \) is unit imaginary number, \( i^2 = -1 \). In this case, time derivatives equal to
\[
\frac{\partial \vec{H}}{\partial t} = i\omega H_a \exp(i\omega t), \quad \frac{\partial \vec{E}}{\partial t} = i\omega E_a \exp(i\omega t).
\]
Then equations (2) are reduced to the form
\[
\nabla \times \vec{H} = \vec{j} + i\mu_0 \omega \vec{E}, \quad \nabla \times \vec{E} = -i\mu_0 \omega \vec{H}, \quad \nabla \cdot \vec{H} = 0, \quad \nabla \cdot \vec{E} = 0,
\]
(5)

**Figure 2.** The scheme of electrolyte jet flow profile in the stream middle part.

Let us introduce the vector potential \( \vec{A}(\vec{r}, t) \) so that \( \vec{B} = \nabla \times \vec{A} \). Then
\[
\vec{E} = -\frac{\partial}{\partial t} \vec{A}(\vec{r}, t),
\]
where \( \vec{r} \) is a radius-vector. From the law of Biot-Savart it follows that
\[
\vec{E}(\vec{r}) = -i\omega \vec{A}(\vec{r}) = -i\omega \frac{\mu_0}{4\pi} \int_V \frac{\vec{j}dV}{|\vec{r} - \vec{r}'|},
\]
(7)
or in terms of complex amplitude
\[
E_a(\vec{r}) = -i\omega \frac{\mu_0}{4\pi} \int_V \frac{j_a dV}{|\vec{r} - \vec{r}'|}.
\]
(8)

In the cylindrical coordinates with axial current \( j_a = j_z l_z, H_a = H_\phi l_\phi, E_a = E_r l_r + E_z l_z \), where \( E_r, E_z, j_z \) are complex radial and axial components of \( \vec{E}, \vec{A} \), respectively, \( H_\phi \) is complex angular components of \( \vec{H}, \vec{A}, l_\phi, l_z \) are basis vectors of the coordinate system. Here we neglect radial part of jet current in comparison with axial part of one.

Let \( r_c = r_c(z) \) be the value of the jet radius at the cross section with the axial coordinate \( z \). Then the jet current density equals to \( j_z(z) = l_a / \pi r_c^2(z) \), where \( l_a \) is current amplitude. Thus, the current density increases inversely with the square of the jet radius. It follows from equations (8) that the real component of the complex electrical intensity at the boundary of the jet
\[
\text{Re} E_r(z) = \frac{l_a}{2\pi\varepsilon_0 \omega r_c^2(z)} \frac{\partial r_c}{\partial z}, \quad \text{Re} E_z(z) = -\frac{l_a}{\pi\varepsilon_0 \omega r_c^2(z)}.
\]
(9)
Graphs of $j_z(z)$ and amplitudes $\text{Re} E_r(z)$ on the jet boundary at $r = r_c(z)$, $I_A = 17$ A, which corresponds to the experiments [16], is showed on figure 2.

It can be seen from figure 2 that the amplitude of the jet current density reaches $\sim 10^6$ A $\cdot$ m$^{-2}$, and the electric field strength on the jet surface is $\sim 10^9$ V $\cdot$ m$^{-1}$ at the local minima of the jet radius. The specified values of the intensity of the RF electric field are enough for gas breakdown around the jet and the formation of annular plasma structures.

4. **Conclusion**

It is found that that annular plasma structures around the electrolytic jet arise in the narrowing of the jet due to high electrical intensity $\sim 10^9$ V $\cdot$ m$^{-1}$ by amplitude.

![Figure 3. Amplitudes of the current density $j_z(z)$ (a) and $\text{Re} E_r(z)$ (b) along the axis Oz with a jet profile showed on figure 3.](image)

**Conflicts of interest**

The authors declare no conflict of interest relating to the material presented in this paper.

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