Plasma Jet Interaction with Dielectric Surface

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Abstract. Propagation of cathode-directed streamer over the helium jet in ambient air is studied in the framework of fluid model and in experiments. The streamer is initiated by applying sinusoidal voltage to the powered electrode inside of dielectric tube and propagates to the direction of treated surface. The gas mixture is calculated with ANSYS Fluent software for helium supply of 4 sl/min. The experimental data on the speed of streamer are in good agreement with calculation results. The reflection of ionization wave from the surface was observed in the experiment and in simulations. It is shown that the reflected ionization wave follows a channel produced by the streamer.

1. Introduction

Cold atmospheric plasma jets are powerful instrument widely used for different applications in medicine [1], agriculture [2] and material surface manufacturing [3]. A streamer propagating from the powered electrode in a dielectric tube delivers the high density plasma to the treated surface, providing the local high electrical field, surface bombardment by ions and enhanced chemical reactions in the mixture of nitrogen, oxygen, water and etc. The large number of publications were devoted to the interaction of cold atmospheric plasma jet with different kinds of surfaces including the tissue. Nevertheless, some important mechanisms of influence of cold atmospheric plasma jet, for example, on human cells live cycle are still missing and are hot topics of recent experimental and theoretical studies. An interesting idea was proposed in Ref. [4]. Authors suggested that a change in permeability of the cell membrane is connected to cell compression due to an increase of osmosis pressure outside the cell as a result of presence ions created by plasma. Recently, the dynamics of different types of cold atmospheric plasma jets is intensively studied in the experiments and simulations (see for example, [5,6] for experiments and [7,8] for simulations).

In this work we study the dynamics of cold atmospheric plasma jet in helium in the experiment and in fluid model simulations and its interaction with a metal surface. The experimental setup is described in details in previous paper [6].

2. Model

The fluid model of discharge includes continuity equations for electrons, ions and mean electron energy $U_e$:

\[
\frac{dn_e}{dt} = \text{div}(\mu_e E n_e + \nabla (D_e n_e)) + \alpha_i n_e n_g - \beta n_e n_i ,
\]

\[
\frac{dn_i}{dt} = \text{div}(\mu_i E n_i + \nabla (D_i n_i) - \nabla n_i) + \alpha_i n_e n_g - \beta n_e n_i ,
\]
\begin{align}
d\left( n_e U_e \right)/dt &= \text{div} \left( \mu_e n_e U_e + \nabla (D_e n_e U_e) \right) + eE \left( \mu_e E n_e + \nabla (D_e n_e) \right) - \nu_e n_e n_g \
\text{and the Poisson equation for the electric potential } \phi \text{ and electric field } E: \\
\text{div } \nabla \phi &= 4\pi e (n_e - n_i), \quad E = -\nabla \phi,
\end{align}

where \( n_e, n_i \) are electron and ion densities, \( V \) is the gas flow velocity, \( n_g \) is the neutral gas density, \( e \) is the elementary charge, \( \alpha, \beta \) are the coefficients of ionization and recombination.

The transport coefficients in the continuity equations for electrons and their mean energy are calculated from the electron energy distribution function (EEDF) \( f_e(\epsilon) \). The EEDF was calculated for a wide range of electric field strengths. The EEDF is found by solving of Boltzmann equation for a wide range of \( E/n_g \). The transport coefficients are:

\begin{align}
D_e &= \frac{1}{n_e} \int \frac{v(\epsilon)}{3n_g \sigma(\epsilon)} f_e(\epsilon) d\epsilon \\
\mu_e &= -\frac{e}{n_e} \int \frac{v(\epsilon)}{3n_g \sigma(\epsilon)} df_e(\epsilon) d\epsilon \\
D_u &= \frac{1}{n_e} \int \frac{v(\epsilon)}{3n_g \sigma(\epsilon)} f_e(\epsilon) d\epsilon \\
\mu_u &= -\frac{e}{n_e} \int \frac{v(\epsilon)}{3n_g \sigma(\epsilon)} df_e(\epsilon) d\epsilon,
\end{align}

where \( n_e = f_e(\epsilon) d\epsilon \), \( v(\epsilon) \) is the electron velocity for the energy \( \epsilon \), \( \sigma(\epsilon) \) is the electron transport crosssection.

For ions the transport coefficients are taken as:

\begin{align}
\mu_i &= \frac{3e}{16n_g \sigma_i} \left( \frac{\pi}{m_i k T} \right)^{1/2} \left( 1 + \frac{9\pi^2 e E}{512n_g k T \sigma_i} \right)^{-1/2} \\
D_i &= \mu_i k T,
\end{align}

where \( k \) is the Boltzmann constant, \( T \) is the neutral gas temperature, \( m_i \) is the ion mass and \( \sigma_i \) its transport crosssection. The electron emission from the dielectric wall inside of the tube due to the electron and ion bombardments is taken into account. The surface charge on the walls of the dielectric tube inside and outside is calculated from the of calculation of electron and ion fluxes on the surface on every electron time step. This surface charge is included in the Poisson equation (4). The equations (1)-(4) we resolved self-consistently over calculation domain shown in figure 1. The radius of calculation domain is \( r_{\text{max}} = 4 \) cm. The metal surface is at \( z_{\text{max}} = 5.5 \) cm.

![Figure 1](image_url)

**Figure 1** Calculation domain (left) and ionization rate distribution at \( t = 3 \) ns.
The dielectric tube has radius of 0.23 cm and length of 2.5 cm. The permittivity of dielectric is 10. The surface is 3 cm apart from the tube. The powered electrode is at $r = 0$, the grounded electrode is shown in light blue. In the experiment, the voltage with 4.5 kV amplitude was applied with the frequency of 25 kHz.

From our experimental observation of plasma jet it is seen that the characteristic length of absorption of photons around a streamer head is approximately 0.1 cm. Therefore, in our simplified model of photoionization we assume that electrons due to photoionization are generated within a semi sphere with radius of 0.1-0.15 cm around the streamer head and the excitation rate determines (with some coefficient $k = 0.1 – 1$) the photoionization rate.

The steady-state gas mixture distribution around the helium jet flowing out from the tube inlet with 4 sl/min in atmospheric air (nitrogen with 22% of oxygen) is shown in figure 2. This mixture was calculated with ANSYS Fluent software and used for calculation of electron transport coefficients, the mean electron energy and the ionization rate by the electron impact.

![Figure 2](image)

**Figure 2** Spatial distributions of fraction of helium (a), nitrogen (b) and oxygen (c) for helium jet, 4sl/min near the tube inlet.

3. Results
At the moment of ‘anode phase’ of applied sinusoidal voltage, a cathode-directed streamer is created near the powered electrode and after a few nanoseconds it starts to propagate along the dielectric wall. In figures, 1 and 3, first steps of the streamer formation and propagation are shown. The streamer has a toroidal shape as it is indicated in figure 3(b) by dotted line. The measured and calculated velocity of the streamer outside of the tube first is 15 km/s, then rises up to 30 km/s and finally drops in front of the surface.
Figure 3 Ionization rate (a),(b) and electrical field distribution (c),(d). Ionization rate in log scale from $3 \times 10^{18}$ to $3 \times 10^{20}$ cm$^{-3}$s$^{-1}$, the electrical field is in kV/cm.

Measured optical emission distribution around the propagated streamer is shown in figure 4. The intensity of emission is given in log scale. The images show dynamics of the streamer approaching the surface and reflected one for times 2 µs, 2.1 µs and 2.2 µs. These times are calculated from the moment of streamer departure from the tube.

Figure 4 Optical emission intensity for $t = 2$ µs (a), 2.1 µs (b), 2.2 µs(c) for $U = 4.5$ kV. Optical emission intensity for $t = 2$ µs(a), 2.1 µs(b), 2.2 µs(c) for $U = 4.5$ kV.

The calculated ionization rate and the potential distribution for approximately the same times are shown in figure 5 for the streamer approaching the surface (a,d) and for initial stages of reflection of the ionization wave from the surface, (b,e) and (c,f). Both experimental and calculated results demonstrate an increase of ionization rate with approaching to the dielectric surface and the averaged velocity of the streamer is 25 km/s.

The ‘seed’ electrons arriving from the zone of helium mixture with air appear due to the photoionization. The electrons gain the energy crossing the streamer head where the electrical field is large and provide the ionization avalanche in a vicinity of the streamer head. So, behind the streamer a channel of plasma forms. Reflected ionization wave to the anode direction flows through the channel made by the straightforward streamer. In figure 5 (d),(e),(f), an elongated potential well occurs from the dielectric tube to the surface, tracking the way of the streamer. Note, that the characteristic times of ambipolar diffusion and recombination is much smaller than the characteristic time of a streamer.

In simulations, we performed a test and removed the channel produced by the streamer, artificially increasing the ambipolar diffusion coefficient. In this case, the reflection of the ionization wave does not take place.

In conclusion, in 2D fluid model simulations and in experiments the dynamics of formation and propagation of the cold atmospheric plasma jet have been studied. The propagation of the cathode-directed streamer inside of dielectrically tube takes place over the dielectric wall. Outside of the dielectrically tube the streamer has a toroidal shape. In the experiment and in simulations the reflection of streamer from the metal surface was registered.
Figure 5 Spatial distributions of ionization rate (a), (b), (c) and potential (d), (e), (f) at different times.

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