Simulation of linearly extended streamer with planar geometry at atmospheric pressure

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Abstract. The cold atmospheric plasma (CAP) jet is used in different applications, for example, in medicine. Typical plasma devices have the cylindrical symmetry. In this work, the new type of device with planar geometry of CAP jet is considered. The initiation of two-dimensional streamer and its propagation from linearly extended electrode to the treated surface is considered with the help of 2D fluid discharge model. Differently to the case of an axially symmetric plasma jet, the streamer head has a plate shape and the ionization wave propagates with considerably larger velocity.

1. Introduction

Nowadays the cold atmospheric plasma (CAP) jet is widely used for the healthcare, such as wound healing, sterilization and even anticancer therapy (see for example, [1]). Low power atmospheric plasma operates at alternative voltage with frequency of tens kHz and amplitude of few kV, without dangerous electric current or thermal damage to the treated tissue and producing chemical species and electrical field necessary for medical treatment and drug delivery. Usually the CAP jet is formed in cylindrical tubes [2, 3]. It was known that the plasma jet is initiated by a streamer, whose leading front propagates at velocities of $10^6$–$10^7$ cm/s. The streamer originates on the powered electrode inside the dielectric tube and moves through a stream of inert gas to the treated tissue, placed on the grounded electrode. The treatment effect is achieved by presence of high electric field, various chemical species, produced by plasmochemical reactions in atmospheric air and delivered to the tissue by plasma jet. In work [2], simulation of streamer propagation in a cylindrical geometry, with axial symmetry, have been performed using the 2D fluid model of electric discharge. The structure of streamer head, ionization rate and electric field distribution were appropriately described by the model. Recently a new geometry of the CAP jet for medical applications was suggested, where a linearly extended powered electrode in a planar dielectric gap are used instead of cylindrical tube, so the plasma jet has a planar geometry. The aim of this work is to consider the initiation and propagation of streamer in such planar geometry, by means of the 2D fluid plasma model, similar to proposed in [2].

2. The physical model and simulation algorithm

The general view of planar CAP jet device is shown in figure 1. The linear powered electrode (on the top of photo) is placed in 2 mm wide and 25 mm depth gap between dielectric walls. A sinusoidal voltage (amplitude 3-7 kV and frequency 10-30 kHz) is applied on the powered electrode and the grounded electrode is 50 mm apart from it.
The streamer ignites during the positive phase of voltage and propagates towards the grounded electrodes for time less than one microsecond.

To simulate the streamer propagation, the fluid discharge model [2, 4] is applied, which includes three continuity equations for electrons, ions and mean electron energy:

\[
\frac{\partial n_e}{\partial t} = \text{div}(\mu_e n_e \vec{E} + \vec{\nabla}(D_e n_e)) + \alpha_e n_e N_g - \beta n_e n_i ,
\]

\[
\frac{\partial n_i}{\partial t} = \text{div}(\mu_i n_i \vec{E} + \vec{\nabla}(D_i n_i)) + \alpha_i n_i N_g - \beta n_e n_i ,
\]

\[
\frac{\partial (n_e U_e)}{\partial t} = \text{div}(\mu_e n_e U_e \vec{E} + \vec{\nabla}(D_e n_e U_e)) + e\vec{E}(\mu_e n_e \vec{E} + \vec{\nabla}(D_e n_e)) - \nu_e n_e N_g - \beta n_e n_i U_e
\]

and the Poisson equation for the electric potential is also solved:

\[
\Delta \phi = 4\pi e(n_e - n_i), \quad \vec{E} = -\nabla \phi .
\]

Here \(n_e, n_i, \mu_e, \mu_i, D_e, D_i\) are the densities, mobilities and diffusivities of electrons and ions respectively, \(U_e, \mu_e, D_e\) are the mean electron energy with its effective mobility and diffusivity, \(E\) and \(\phi\) are the electrical field vector and potential, \(N_g\) is the gas density, \(\beta\) is the electron-ion recombination coefficient. The transport coefficients together with ionization coefficient \(\alpha_i\) and electron unelastic collision rate coefficient rate \(\nu_i\) are obtained by solving the Boltzmann equation for local \(E/N\) value.

The detailed description of the model is published in [2]. Also the photoionization process in the region of streamer head is added to the model, as described in [2].

The simulation domain for planar-geometry streamer is shown in figure 2. The domain is symmetrical on Y-axis and extended in Z direction. The grounded electrode is covered by 5 mm thick layer of water or PBS layer.

The ignition of CAP jet with planar geometry. Figure 2. The scheme of simulation domain: 1 – powered electrode, 2 – dielectric wall of the gap, 3 – grounded electrode, 4 – water or PBS layer.
3. Results and discussion

The streamer initiates as a wave of ionization moving from the powered electrodes inside the dielectric gap. The propagation of ionization wave is shown in figure 3. The velocity of planar streamer head is extremely large inside the gap and achieves $10^8$ cm/s at the first 40 ns of streamer propagation. After this, when the ionization wave reach the escape from the gap, its velocity strongly decreases (see the moments 48-60 ns of streamer motion in figure 3) and after this the ionization wave propagates in the atmosphere with more spatially extended structure (see moments 80-250 ns). The wave velocity in the atmosphere is less than $10^7$ cm/s. The spatial region of large electrical field and strong ionization becomes wider in both directions, but their magnitudes diminish. It is more clearly seen in figure 4, where the electrical potential $\varphi$ and ionization rate are plotted along the $Y$-axis. The motion of streamer significantly decelerates at the exit from the gap for a few nanoseconds, but then goes on with slower velocity, and also smaller electric field and ionization rate magnitudes in the streamer head. Note also that the maximal gradients of $\varphi$ and magnitudes of ionization rate are shifted from the $Y$-axis, thus not laying in the symmetry plane. This is similar to the results of axially symmetric model,

![Figure 3](image-url)
where these maximal magnitudes were also aside the axis of symmetry, thus streamer head having a toroidal form [2]. In the gap, the streamer head fills all space between walls. After escaping the gap, the head firstly remains 0.2 cm in width, but tends to extend when reaching the grounded surface (see figure 3, $t = 250$ ns).

The main difference in simulation results compared with axially symmetric streamer is much larger velocity of streamer head propagation, which in [2] was $10^7$ cm/s in the dielectric tube and $10^6$ cm/s in the atmosphere. The presented simulations in planar geometry shows velocity $7\cdot10^7$ cm/s in the dielectric gap and $8\cdot10^6$ cm/s in the atmosphere. This difference may be due to linear extension of large electric field region in Z-direction.

The maximal ionization rate in the streamer head has the similar order of magnitude as for axially symmetric case, exceeding $10^{21}$ cm$^{-3}$/s in gap. It diminishes to $10^{19}$ cm$^{-3}$/s when crossing the gap exit and then gradually rises to $10^{20}$ cm$^{-3}$/s after departure from the gap (figure 4b).

In conclusion, the 2D fluid model simulations of planar streamer propagation in application to CAP treatment of biological tissues have been performed. The structure of two-dimensional, linearly extended streamer was considered, its evolution during propagation through linear gap and extension into atmosphere was studied. The main difference with streamer simulations in axially symmetric geometry is the much larger velocity of propagation.

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![Figure 4. The profiles of electric field potential (a) and ionization rate (b) for the different time moments of streamer propagation, 32-250 ns, plotted along the Y-axis.](image)