Electric field distributions along helium plasma jets

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Abstract: Results of simulations of streamers propagating along the atmospheric-pressure helium plasma jets ejected from a thin tube into ambient air are presented. The computational model includes the equations governing the helium–air mixture composition along and across the jet, as well as the equations, describing streamer propagation in the mixture, for the electric field and the charged species densities. Streamer velocity and spatial–temporal profiles of plasma parameters are obtained for various values of the helium flow rate. It is shown, in agreement with available experimental data, that the electric field values in the heads of streamers increase nearly linearly with the distance from the tube exit and that the slope of this dependence decreases with the growth of the helium flow rate.

1 Introduction

Atmospheric-pressure plasma jets (APPJs) formed by discharges, inside thin dielectric tubes, in flows (usually of inert gases) ejected into ambient air have recently attracted great interest as one of the most perspective generators of non-thermal plasma – sources of production of reactive species for various applications, such as surface treatment, biotechnologies, plasma medicine etc. [1, 2]. The APPJs fed by repetitive voltage pulses are typically composed of plasma bullets – guided streamers propagating along the jets [3]. Parameters of streamer plasma are favourable for the production of reactive species [4], both inside discharge tubes and in the effluent (in the mixture of plasma-forming gas with surrounding air), up to the contact of plasma jet with target surfaces, thus allowing treatment of targets by short-living reactive species. The efficiency of the generation of reactive species is governed, to a great extent, by the values of an electric field [4]. In this respect, much attention is paid to measurements of electric fields and streamers inside APPJs. For this purpose, various methods have been used, based on the intensity ratio of the first negative and second positive systems of N₂ radiation [5], polarisation-dependent Stark splitting and shifting of visible helium lines [6–11], Pockels technique [12–16], electric field-induced second harmonic generation method [15, 16]. A number of measurements give, in the region of effluent along the helium APPJ axis [6, 8–11, 16]. Similar results have been obtained also in computations [17–20]. It has been observed [8] that the rate of increase of the electric field with the growth of the distance from the tube end is governed by the gas flow rate. This work is aimed at the computational study of the effects of gas flow rate variation on the profiles of the electric field inside helium APPJs, as well as on other plasma jet characteristics.

2 Model

Propagation of streamers along helium jets passing through a thin tube and injecting into ambient air is considered. A streamer is initiated and moves initially along the jet axis inside the tube, in pure helium. Outside the tube, mixing of helium flow with surrounding air takes place, so that the streamer, after passing the tube exit, continues propagation in a helium–air mixture, non-uniform both in axial and radial directions. For streamer simulation, the 2D streamer model [17, 21] is used. It includes the coupled system of equations for the electric field and for the densities of charged and neutral species. The electric field $E$ is governed by the Poisson equation for the potential $\Phi$:

$$E = -\nabla \Phi, \quad \nabla^2 \Phi = -4\pi e(n_p - n_e)$$

where $n_p$ and $n_e$ are the number densities of positive ions and electrons. The values $n_p$ and $n_e$ of the charged species densities are governed by the transport equations:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j V_j) = F_j + S_{ph},$$

where $n_j$, $V_j$ and $D_j$ are the number densities, mobilities and diffusion coefficients, respectively, for species of sort $j$, the terms $F_j$ are the rates of production of species $j$ in kinetic processes and the term $S_{ph}$ describes the production of precursor electrons and ions ahead of the streamer front due to photoionisation. The model also includes the balance equations like (2), without transport terms, for the densities of neutral species: excited helium atoms He²⁺ and exoclymer molecules Heᵐ⁺. The kinetic scheme involves reactions of direct and stepwise ionisation of air molecules and helium atoms by electron impact, conversion of He²⁺ to He⁺, Penning processes of ionisation of air molecules in collisions with He⁺ and Heᵐ⁺, electron–ion recombination. The kinetic and transport parameters for electrons in helium–air mixtures, versus the local values of the reduced electric field $E/n$ (where $n$ is the gas density) and of the molar fraction of air in the mixture, are calculated using the BOLSIG⁺ code [22]. The term $S_{ph}$ is evaluated in the assumption that the precursor charged species are produced, ahead of the streamer front, at absorption by air molecules of ionising radiation emitted, in the streamer front region, by exoclymer molecules Heᵐ⁺.

Previously to streamer simulations, the mixture composition inside the jet effluent, versus the axial $x$ and radial $r$ coordinated, is calculated by solving the system of continuity, momentum and mass diffusion equations (the electrohydrodynamic effects caused by streamer plasma and the effects of gravity on the mixture composition are neglected):

$$\frac{\partial (\rho u)}{\partial x} + \frac{1}{r} \frac{\partial (\rho r v)}{\partial r} = 0,$$

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Here \( \rho \) is the gas density, \( u \) and \( v \) are the axial and radial gas velocities, \( f \) is the mass fraction of helium, \( \mu \) is the viscosity and \( D \) is the diffusion coefficient. These equations, written in the boundary layer approximation (neglecting the effects of viscosity and diffusion along the axial direction), are valid for laminar gas flow with high Reynolds numbers, typical for plasma jet conditions. A parabolic profile of the axial velocity at the tube exit is assumed: 
\[
\alpha(0, r) = 2\alpha(1 - r^2/R_{jet}^2),
\]
where \( R_{jet} \) is the initial jet radius, equal to the inner radius of the tube, and \( \alpha_0 \) is the mean helium flow velocity. The spatial profile of the air molar fraction in the effluent is governed by two factors: inner radius \( R_{air} \), and helium flow rate \( G = \pi R_{jet}^2 \alpha_0 \). The spatial profiles of the mixture composition in the jet effluent have been calculated, at \( R_{jet} = 0.2 \) cm, for three values of the helium flow rate: 2.8, 5.6 and 11.2 l/min. [Note that the Reynolds number at the highest \( G \) is around 400, corresponding, in accordance with [23], to the laminar-to-turbulent transition regime. However, for the initial part of the jet (not too far from the tube exit), considered in this work, the laminar approach is still valid.]

The simulation of streamers starting from the axial position \( x = 0 \) is performed. The tube end is placed at \( x = 0.5 \) cm, so that in the region \( 0 < x < 0.5 \) cm streamers propagate inside the tube in pure helium. The spatial profile of the applied electric field (that is, the field in the absence of space charges produced by the streamer) is taken, similar to the approach used in [17, 21], the same as that produced by a conducting sphere, having the positive, independent of time, potential \( U = 6 \) kV, with a radius of 0.5 cm and surface placed at \( x = 0 \). As the initial conditions, uniform spatial distributions of the number densities of charged species (electrons \( n_{e0} \) and positive ions \( n_{p0} \)) at the time moment \( t = 0 \) are taken, at the level typical for repetitive frequencies in kHz range [21]: \( \alpha_0 = n_{e0} = 10^9 \) cm\(^{-3} \). As boundary conditions, zero derivatives of charged species densities at all the boundaries of the computational region are taken.

### 3 Results

In Fig. 1 the distributions of axial values of electric field \( E_{ax} \) and the number density of electrons along the symmetry axis, calculated for \( G = 2.8 \) l/min, are presented at several time moments during the streamer propagation. The line at \( t = 0 \) shows the applied electric field. The maximums of \( E_{ax} \) corresponding to positions of the streamer front, increase with \( x \), varying in the range 10–20 kV/cm, in agreement with usually measured data in helium APPJs. The density of electrons \( n_{eax} \) at the axis also increases with \( x \) (note that variation of \( n_{eax} \) behind the streamer front, in the channel, with time is rather weak).

The maximum electric field \( E_0 \) shown in Fig. 1a, grows, outside the tube, with \( x \) nearly linearly, in agreement with the experiments mentioned above. The \( E_0 \) value at a given axial position is higher than \( E_{ax} \). Such behaviour reflects the ring-shaped streamer structure typical for helium APPJs, when radial positions of maximums of electric field and electron density are shifted from the axis [3].

The ring-shaped streamer structure is demonstrated in Fig. 2 where the radial profiles of electron density in the streamer channel at the axial positions are given. With the growth of the distance from the tube end, the radial positions of the maximum electron density \( n_{eax} \), become closer to the jet axis, and the values of \( n_{eax} \) increase, in line with the growth with \( x \) of \( E_0 \).

Note that radial positions of \( n_{eax} \) maximums shown in Fig. 2 are close to the radial positions where the axial molar fraction \( X_{ax} \) in the mixture is equal to \( 10^{-2} \), like in simulations [21, 24].

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**Fig. 1** Profiles of electric field

(a) and electron density, (b) along the jet axis at various time moments (solid lines) and the maximum electric field vs axial position (dotted line), for helium flow rate of 2.8 l/min

**Fig. 2** Radial profiles of electron density in the streamer channel, for helium flow rate of 2.8 l/min, at the axial positions \( x = 0.5 \) (1), 1.0 (2) and 1.5 (3) cm

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increase of the gas flow rate, the radial positions corresponding to \( X_{\text{air}} = 10^{-2} \) shift to larger distances from the tube exit.

Radial profiles of the air molar fraction and electron density in the streamer channel, at the same axial position \( x = 1.5 \text{ cm} \), are presented, for various helium flow rates, in Fig. 3. At given \( x \), the radial positions of \( n_e \) maximums, corresponding to the radial positions \( X_{\text{air}} = 10^{-2} \), are farther from the axis at higher \( G \).

In Fig. 4 the streamer propagation velocity \( V \) (that is the velocity of the streamer front – the region of the maximum electric field) is given versus the streamer length \( L \) (the distance between the positions of streamer front and start), for various \( G \). Decreasing weakly inside the tube (at \( L < 0.5 \text{ cm} \)), the velocity passes a minimum at some distance \( x_{\text{min}} \) from the tube exit and increases at larger \( x \). The axial position \( x_{\text{min}} \) increases with the growth of \( G \), that is with the growth of the distance from the tube exit where a considerable mixing of helium with surrounding air occurs.

Fig. 5 shows the maximum electric field \( E_h \) versus the axial position, for various helium flow rates. Like streamer velocity, \( E_h \) increases faster for lower \( G \), that is for faster helium–air mixing. (This effect can be due to the fact that the higher content of the air in the mixture requires a stronger electric field to provide ionisation of the gas in the streamer front.) Such \( E_h \) behaviour agrees qualitatively with experimental data (see Fig. 2 in [8]). Note that higher \( E_h \), at the given axial position, for lower \( G \) is responsible for larger \( n_e \) maximums (Fig. 3b).

4 Conclusion

Computations of streamer dynamics in helium APPJs ejected into ambient air have been performed for various values of the helium flow rate \( G \). It is shown that the increase of gas flow rate, resulting in the growth of the mixing length, affects the spatial profiles of plasma parameters. In particular, the larger is \( G \) the smaller (at given axial position) are the streamer velocity, maximum electron density and electric field, and the larger is the radius of the ring-shaped streamer structure. The calculated values of the electric field in the heads of streamer heads increase, in the effluent region adjacent to the tube exit, nearly linearly with the distance from the tube end, the slope of this dependence lowering with the growth of the helium flow rate, similarly to experimental data.

5 Acknowledgments

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6 References

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