Simulation of streamer dynamics in atmospheric pressure plasma jets

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Abstract: The results of numerical simulation of streamer dynamics in atmospheric-pressure plasma jets in helium-argon mixtures are presented. Calculated velocities of streamer propagation agree with published data on the velocities of plasma bullets.

Keywords: streamers, plasma jet.

1. Introduction

The atmospheric pressure plasma jets (APPJ) are actively studied as an effective source for production of non-thermal plasmas. It has been found that the jet is composed of bullet-like plasma volumes traveling with velocities $10^6$-$10^8$ cm/s [1-8]. To explain properties of the plasma bullets, a streamer mechanism of their propagation has been proposed [2]. An analogy between the APPJ and streamers has been supported by recent experiments [3].

In this paper the results of numerical simulation of streamer dynamics in APPJ for conditions of experiment [3] are presented. Calculated streamer velocities are compared with the measured velocities of plasma bullets.

2. The model

To simulate streamer propagation, a simplified model is used that assumes the streamer radius $R_{str}$, a variable parameter of the model, to be constant along the streamer length. (It has been shown [9] that this approach gives, at appropriate choice of $R_{str}$, the streamer velocities close to those obtained on the basis of more accurate two-dimensional simulations.) The model includes the transport equations for the number densities of electrons and positive ions written in drift-diffusion approximation. The electric field is evaluated in assumption that the streamer space charge is uniformly distributed along the radial coordinate $r$ at $r < R_{str}$ and equals to zero at $r > R_{str}$ [10].

Calculations are performed for streamers in atmospheric-pressure helium-argon mixtures, at various values $X_{Ar}$ of Ar molar fraction. The kinetic and transport coefficients for electrons in the mixtures, as functions of the reduced electric field, are calculated with the BOLSIG code [11].

The Laplacian electric field $E_L$ at the streamer axis is evaluated as that produced by a positively charged thin tube electrode (the axis of the electrode coincides with the streamer axis), with diameter $a$ and length $d$, the distribution of electric charge density along the tube being taken in accordance with the numerical results [12].

The model does not include a photo-ionization source of charged species ahead of the streamer front; it is assumed that the streamers propagate in a weakly pre-ionized gas, the initial number density $n_0$ of charged species being a variable parameter.

Fig.1 Ionization coefficient and drift velocity of electrons versus reduced electric field in helium-argon mixtures
3. Results
The considered helium-argon mixture compositions are those studied in [3]: the molar fraction of Ar is taken in the range $0.01 < X_{\text{Ar}} < 0.2$.

In Fig.1 the calculated values of ionization coefficient $\alpha/n$ and drift velocity of electrons $V_{\text{dr}}$ are shown versus the reduced electric field $E/n$ for various helium-argon mixtures. It is seen that addition of argon leads, at high $E/n$, to increase of $\alpha/n$ and decrease of $V_{\text{dr}}$.

Simulations of streamer dynamics have been performed for conditions close to those of experiment [3], for the electrode (tube) diameter $a = 0.4$ cm and length $d = 0.6$ cm. [Note that the set-up [3] includes the second, grounded electrode positioned at the upstream side of the jet, at the distance about 1 cm from the positively charged electrode. In our simulation the electric field at the downstream side of the jet (the region of streamer propagation) is evaluated without account of the effects of both this electrode and the space charge of plasma positioned inside the dielectric capillary between the electrodes. The effect of the capillary on the electric field is also neglected.]

In Fig.2 the distributions of reduced electric field $E/n$ and number density of electrons $n_e$ at the streamer axis along the direction of streamer propagation $z$ (position $z = 0$ corresponds to the downstream end of the electrode) are given for several time moments. The shown data correspond to argon molar fraction $X_{\text{Ar}} = 0.05$, streamer radius $R_{\text{str}} = 0.1$ cm, background electron number density $n_0 = 10^5$ cm$^{-3}$, and electrode potential $U = 11$ kV. Note that the maximum values of reduced electric field in the streamer head, about 120-130 Td, are 4-5 times lower than those typical for streamers in atmospheric-pressure air (e.g. [9]), while the electron number density in streamer channel, about $10^{13}$ cm$^{-3}$, is more than an order of magnitude lower than that in air.

In Fig.3 the calculated position $L$ of the streamer head, counted from the downstream end of the electrode, versus time is given (lines) for $X_{\text{Ar}} = 0.05$, $R_{\text{str}} = 0.1$ cm, $n_0 = 10^5$
cm$^{-3}$, at three values of the electrode potential, $U = 10, 11$ and 13 kV. The experimental data [3] for $X_{Ar} = 0.05$ and $U = 11$ kV are also shown (points). At $L < 2$ cm the calculated streamer head position agrees well with the experiment; at larger $L$ the measured streamer velocity is lower than the calculated one, possibly due to the effect of mixing of the He-Ar jet with surrounding air.

In Fig.4 the calculated streamer velocity $V$ is given versus the position of streamer head, for conditions of Fig.3. It is seen that maximum of $V$ is reached at some distance, exceeding 1 cm, from the electrode. (This result agrees qualitatively with the observations [2] where the maximum of plasma-bullet velocity is achieved at the distance 2-3 cm from the nearest electrode.) The increase of $U$ from 10 to 13 kV results in the growth of calculated streamer velocity about twice.

Results of calculations show that variations of both $R_{str}$ and $n_0$ do not affect substantially the velocity of streamer propagation.

Fig.4. Streamer velocity versus position of streamer head in the mixture He:Ar = 95:5 at various values of the electrode potential.

The effect of the mixture composition on streamer propagation velocity is demonstrated in Fig.5 where the calculated streamer velocity versus the position of streamer head is given for $R_{str} = 0.1$ cm, $n_0 = 10^5$ cm$^{-3}$, $U = 11$ kV, for three various helium-margon mixtures. It is interesting to note that the dependence of streamer velocity on the argon molar fraction is non-monotonous; in the mixture He:Ar = 95:5 the streamer propagates faster than in those containing 1 and 20 percents of argon.

It is noted in [3] that at the argon molar fraction varying in the range $0.01 < X_{Ar} < 0.2$ and the applied voltage varying in the range $10 < U < 13$ kV the measured plasma-bullet velocities are in the range $(4-8) \times 10^7$ cm/s. Calculated values of the mean streamer velocity for these ranges of $X_{Ar}$ and $U$ agree with the experimental data.

Fig.5. Streamer velocity versus position of streamer head in various He-Ar mixtures at $U = 11$ kV.

In recent work [8] it has been revealed that in helium APPJ the intensity of radiation emitted by plasma bullets has a ring structure, the maximum of intensity being observed at some distance from the jet axis. Basing on this observation, the authors of [8] conclude that the plasma bullet is hollow and propagates along the interface of two media, helium and surrounding air, as a surface ionization wave. Note that another explanation of the hollow structure of plasma-bullet radiation is, in our opinion, more probable: as in mixtures of helium with surrounding air the radiation of nitrogen is much stronger than that of helium, the maximum of radiation intensity is reached at the periphery of the jet, in the region where a mixing of helium jet with air takes place, so that a sufficient amount of nitrogen is present in the mixture.

The length of plasma bullet propagation is governed mainly by the jet length, i.e. by the distance that the jet propagates without noticeable mixing with air in the near-axial region. It can be shown that the increase of laminar jet velocity results in growth of the jet length. At sufficiently high values of the Reynolds number a transition to turbulent flow regime occurs, so that the following increase of jet velocity leads to shortening of the jet length because of much faster mixing. Note that such character of the dependence of the length of plasma bullet propagation on the helium flow rate, with a maximum in the region of laminar-to-turbulent transition, has been observed in [8].
4. Conclusion

Streamer velocities obtained in our simulations for conditions of experiment [3] agree with the measured velocities of plasma bullets. This agreement supports the assumption on the streamer-like nature of the APPJ.

References