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On streamer interaction in a pulsed positive corona discharge

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Abstract. An approximate method is presented to take account of interaction of positive streamers simultaneously propagating between a wire and a plate. The method is based on a quasi-2D positive streamer model modified by inclusion in the expression for electric field of an additional term describing the field of charges of all streamer channels in the gap. All streamers are assumed to be identical and to move parallel to each other to the plate from points equidistantly distributed along the wire surface. The model is used for calculation of streamer dynamics in atmospheric air for conditions under which simultaneously propagating streamers have been observed. It is shown that taking account of streamer interaction improves the agreement of the calculated dependence of streamer velocity on its length with the experimental one.

1. Introduction

Pulsed corona discharges are being actively studied in connection with their plasma chemical applications, such as ozone generation from air and oxygen and removal of toxic agents from flue gases and from polluted air. Chemically active particles are produced in thin plasma channels (streamers) propagating in a discharge gap. For prediction of the efficiency of plasma chemical processes in various experimental situations the modelling of streamer parameters is of great importance. The description of pulsed corona discharges is usually based on single-streamer models. In experiments, however, simultaneous propagation of several streamers is often observed. For example, pulsed positive corona discharge in wire–plate electrode configurations typical for plasma chemical applications has the structure of a set of streamers starting from the anode almost simultaneously, the distances between neighbouring streamers being 0.1–0.3 cm [1]. The problem of prediction of discharge structure is very complex; for its solution the development of 3D models is needed. However, if experimental information on streamer structure is available it can be used to account for streamer interaction in simpler models.

One of the factors related to mutual influence of simultaneously developing streamers can be easily taken into account in an electric circuit equation by adopting the total current as a product of the streamer current (calculated using the single-streamer model) and the number of streamers in the gap. In this approximation, streamer interaction may be essential only for circuits with large enough ballast resistances (comparable with gap resistances).

Apart from interaction through the external circuit, simultaneously propagating streamers influence each other due to the change in electric field distribution inside the gap caused by volume charges of streamer channels. In this paper the method of taking account of this effect in a quasi-2D positive streamer model is presented. The expression for electric field is modified by inclusion of an additional term describing the field of charges of all streamer channels in the gap. All streamers are assumed to be identical and the distances between neighbouring streamers are taken to be equal.

2. The model

The adopted scheme of streamer propagation in wire–plate electrode configuration is given in figure 1. The thin wire (anode) is positioned along the x axis; the z axis is directed normally to the plate (cathode) located at $z = d$. All streamers are assumed to start simultaneously from the anode (from points $x = 0, \pm a, \pm 2a, \ldots$) and to move in the x–z plane. The development of a streamer that starts from $x = 0$ will be considered.

There is no simple analytical expression for the electric field generated by charge located inside the wire–plate gap. An approximate expression for electric field in the x–z plane can be obtained by use of the method of reflections. In this approximation, reflections of space charge in planes $z = 0$ and $z = d$ are taken into account. Estimates show that, for conditions $a \ll d$, enough accuracy is obtained by taking account of one reflection in each of the planes. This approach gives the following equation for the z component of electric field along the

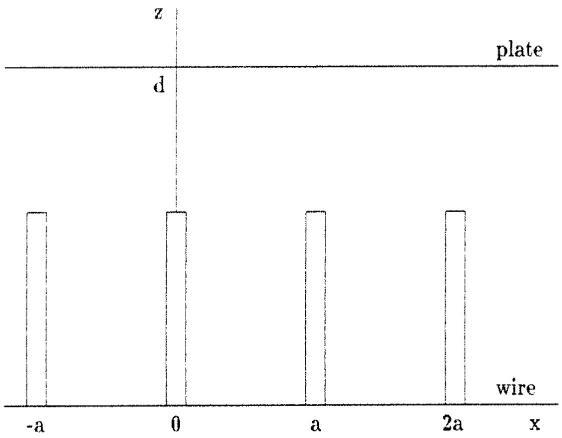

Figure 1. The scheme of streamer propagation.

line $x = 0$ due to the space charge of a neighbouring streamer moving from $x = a$:

$$E^{(a)}(z,t) = \int_0^{l(t)} \rho(z',t)\,\mathrm{d}z'[\psi(z-z') - \psi(z+z'-2d) - \psi(z+z')] \qquad (1)$$

$$\psi(y) \equiv \frac{y}{(a^2+y^2)^{3/2}}$$

where $l(t)$ is the streamer length at time moment t and $\rho(z',t)$ is the space charge distribution along the streamer per unit length. In derivation of equation (1) the relation $R \ll a$ is taken into account, where R is the streamer dimension normal to the z axis (the streamer radius). The two last terms in integral (1) correspond to reflections of streamer charge in planes $z = 0$ and $z = d$.

The space charge of the streamer channel gives the main contribution to integral (1). The space charge density at the streamer head is greater than in its channel but because of the small size of the head its field sharply decreases with distance and does not influence the propagation of neighbouring streamers. The results of calculations of streamer propagation in short gaps (up to several centimetres in atmospheric air) show that the space charge distribution $\rho(z,t)$ in the streamer channel weakly depends on z (see below). So the expression (1) can be simplified by introducing the mean space charge density $\bar{\rho}(t)$:

$$E^{(a)}(z,t) = \bar{\rho}(t) f(a) \qquad \bar{\rho}(t) = \int_0^{l(t)} \rho(z',t)\,\mathrm{d}z'/l(t) \qquad (2)$$

$$f(a) = \chi(z-l) + \chi(z+l) + \chi(2d-z-l) - \chi(2d-z) - 2\chi(z)$$

$$\chi(y) \equiv (a^2+y^2)^{-1/2}.$$

The sum of contributions of all simultaneously developing streamers on both sides of the streamer under consideration gives the electric field

$$E_{int}(z,t) = E^{(a)}(z,t) + E^{(-a)}(z,t) + E^{(2a)}(z,t) + \cdots \qquad (3)$$
$$= \bar{\rho}(t)[(f(a) + f(-a) + f(2a) + \cdots].$$

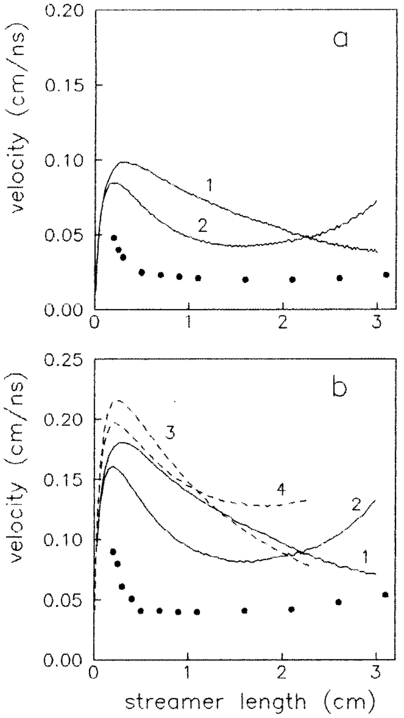

Figure 2. The dependence of streamer velocity on its length for V = 20 (a) and 25 kV (b). Points are experimental data [1], curves are calculations without (1, 3) and with (2, 4) account taken of streamer interaction for a = 0.2 cm and R = 0.02 cm (1, 2) and 0.01 cm (3, 4).

The summation in (3) can be performed approximately by replacing the sum by an integral. For the case in which the wire length $L \gg d$ the upper limit in the integral may be set equal to infinity. It gives

$$E_{int}(z,t) = \frac{2\bar{\rho}(t)}{a} \ln\left(\frac{\Phi^2(z)\Phi(2d-z)}{\Phi(z-l)\Phi(z+l)\Phi(2d-z-l)}\right) \qquad (4)$$

$$\Phi(y) \equiv a + (y^2+a^2)^{1/2}.$$

The values of $\bar{\rho}(t)$ and $l(t)$ in (4) are determined during the process of calculation of streamer motion in a self-consistent electric field equal to the sum of the field created by the electrodes (the Laplacian field) E_L, the field E_s generated by the space charge of the streamer under consideration and the field E_{int} of the charges of all other streamers developing in the gap.

Note that, in long gaps, the distribution of $\rho(z)$ along the streamer channel may be non-uniform. In this case the value of E_{int} can be obtained by numerical integration (1) and summation (3).

The expression for additional electric field can be incorporated into any model developed for calculation of single-streamer propagation. The description of streamers in non-uniform electric fields is usually based on quasi-2D models [2–6]. In these models, distributions of plasma parameters in the streamer channel in the radial direction (normal to the direction of streamer propagation) are taken to be the known functions and are usually stepwise. The streamer radius R is assumed to be constant along

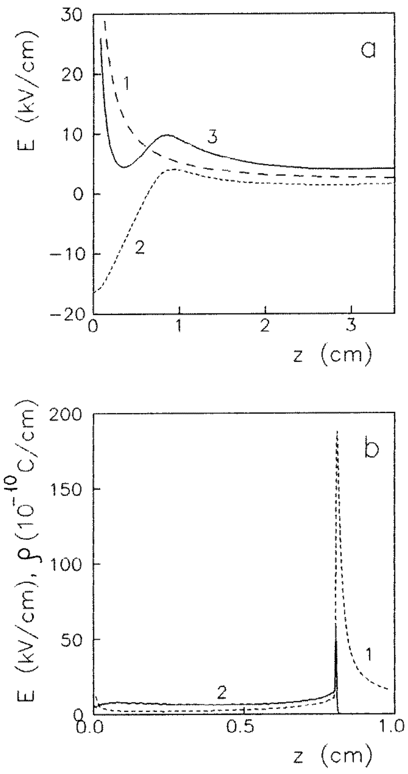

Figure 3. Distributions of electric field components (*a*) and of total electric field and linear space charge (*b*) along the streamer axis for V = 25 kV, a = 0.2 cm and R = 0.02 cm, with streamer length l = 0.8 cm: (*a*) 1, E_L; 2, E_{int}; and 3, E_Σ; (*b*) 1, E; and 2, ρ.

the streamer length, the value of R being the variable parameter. Often the value of R is used that corresponds to avalanche–streamer transition (for atmospheric air it is about 0.003–0.005 cm). Recent studies of streamer structure have given significantly greater values of R. By optical measurements of the radial distribution of streamer radiation intensity in a point–plane electrode configuration [7] the value $R = 0.085$ cm has been obtained. Measurements under experimental conditions [1] have shown that the optical radius of primary streamers is about 0.02 cm [8]. Calculations of streamer dynamics in uniform fields with use of a full 2D model [9] have revealed that the radial dimensions of distributions of different plasma parameters in a streamer channel differ considerably, values of R lying within the interval 0.02–0.04 cm.

Though quasi-2D models cannot provide an accurate quantitative description of streamer parameters, they adequately reproduce many features of streamer formation and propagation. In this work a quasi-2D model [5] for estimation of the effect caused by streamer interaction is used. It includes continuity equations for charged particles (electrons, positive and negative ions)

$$\partial n_j/\partial t + \partial(n_j v_j)/\partial z = J_j \tag{5}$$

where n_j and v_j are densities and velocities and J_j is the sum of contributions of kinetic processes (collisional ionization, attachment of electrons, photo-ionization) for particles of sort j. The values of rate constants of the processes with participation of electrons are determined by local values of the electric field. The dependences of transport coefficients and rate constants of kinetic processes on the field for air are taken in accordance with [10], the photo-ionization term is calculated using the model [11]. For solution of continuity equations a modified flux-corrected transport method [12] on an adaptive mesh is used. The value of the electric field E_s is calculated by the method of discs [13]. The space charge inside the streamer channel is assumed to be distributed uniformly in the radial direction.

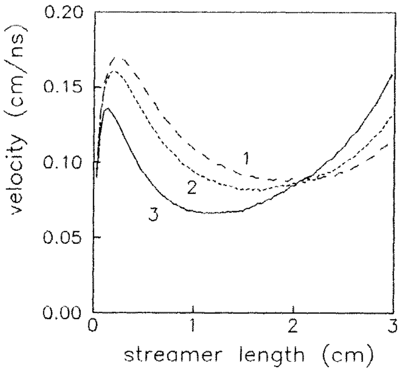

Figure 4. The dependence of streamer velocity on its length for V = 25 kV, R = 0.02 cm and a = 0.3, 0.2 and 0.1 cm (curves 1, 2 and 3, respectively).

3. Results of the calculation

Calculations of streamer dynamics in atmospheric air were performed for the conditions of experiment [1] (for wire radius $R_w = 0.03$ cm, gap length $d = 3.5$ cm, applied voltages $V = 20$ and 25 kV). The model involves two parameters, streamer radius R and the distance between neighbouring streamers a, that can be varied. For parameter R the value 0.02 cm is used, corresponding to the data of the optical measurements [8]. For comparison the results of a calculation with $R = 0.01$ cm are also given. The distance between streamers is varied around the value 0.2 cm, in accordance with experimental data [1] (note that the number of streamers per unit length of the wire weakly depends on the applied voltage [8]).

The voltage across the gap is assumed to have the form of a stepwise pulse with an indefinitely short rise time. This assumption corresponds to the conditions of the experiment [1], in which fast rising pulses were used and formation of streamers began almost simultaneously when the value of applied voltage was close to its maximum.

In figure 2 experimental [1] and calculated streamer velocities as functions of streamer length are shown. In the case of single-streamer propagation the streamer velocity, after a sharp rise in the region of high Laplacian electric field near the anode, decreases monotonically with length. Taking account of streamer interaction gives a velocity dependence having its minimum in the middle of the

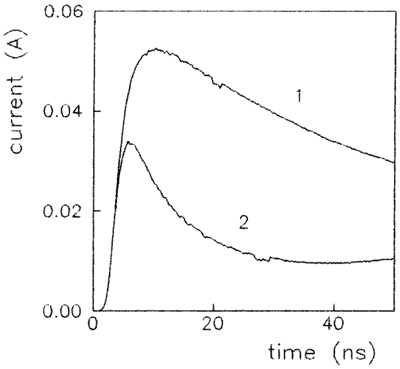

Figure 5. The dependence of current per streamer on time for V = 20 kV and R = 0.02 cm. Curve 1, single-streamer propagation; and curve 2, simultaneously developing streamers, a = 0.2 cm.

gap. On approaching the cathode the value of the electric field E_{int} increases due to the influence of charge reflection leading to growth of streamer velocity. Note that, in the case of single-streamer propagation, calculations also give an increase in streamer velocity. However, it occurs close to the cathode, at distances less than 0.2 cm (not shown in figure 2), for which, for a correct description of the streamer dynamics, streamer–cathode interaction must be taken into account [4].

Comparison of the results obtained for two values of streamer radius R (figure 2(b)) shows that the change in velocity due to streamer interaction is greater for greater R, because an increase in R leads to a growth in linear space charge ρ. However, the character of the change in dependence of the velocity on streamer length is the same for both values of R.

The results obtained taking account of streamer interaction are in better accordance with experimental data than are the values calculated in the single-streamer case. Calculated values of streamer velocity are two or three times greater than obtained in the experiment [1]. The reason for this discrepancy may be the approximate nature of the quasi-2D model used. Figure 2(b) shows that the results of calculations for $R = 0.02$ cm agree better with experiment than do those for $R = 0.01$ cm. The too sharp (in comparison with experiment) increase in calculated streamer velocity near the cathode may be explained by the fact that, in the experiment, not all of the simultaneously developing streamers reach the cathode. Some of them stop in the middle of the gap. So, for values of the streamer length close to the gap distance, the role of streamer interaction is overestimated in the adopted scheme. Another cause of overestimation of streamer interaction is the assumption that all streamers move in the same plane. Deviation from the plane leads to an increase in the mean distance between the streamers with growth of their length.

In figure 3 the distributions of electric field components E_L and E_{int}, their sum (effective external field for streamer propagation) $E_\Sigma = E_L + E_{int}$, the full electric field $E = E_\Sigma + E_s$ and the linear space charge density ρ along the gap are shown under the conditions of figure 2(b) (for $R = 0.02$ cm) at the time moment corresponding to streamer length 0.8 cm. Streamer interaction increases the field in front of the streamer head and decreases it in the region of the channel. It is seen that the distribution of ρ along the channel is nearly constant, justifying the possibility of introducing the mean space charge density $\bar{\rho}$ in the equation (2).

The results of calculation for various values of streamer number per unit wire length (for various values of distance a) are given in figure 4. The role of streamer interaction grows with decreasing a.

Not only the streamer velocity but all other streamer parameters such as the charge transferred by one streamer and the number of generated active particles differ between these two cases. In figure 5 the calculated streamer currents as functions of time are shown. For simultaneously developing streamers the current per streamer is considerably less than the single-streamer current.

Note that one more factor related to streamer interaction has to be considered. It is the enhancement of concentration of photoelectrons in front of a streamer under consideration due to deposition of ionizing radiation from neighbouring streamers. As the calculations performed taking account of this factor have shown, its influence on streamer dynamics is negligibly small.

4. Conclusions

The results presented above show that taking account of interaction of streamers simultaneously propagating in the discharge gap essentially influences streamer parameters (the dependence of velocity on streamer length, current per one streamer and so on). Taking into account this effect for conditions under which experimental information on the discharge structure is available can improve the description of discharge characteristics.

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