XXVIIth ICPIG, Eindhoven, the Netherlands, 18-22 July, 2005

Streamer dynamics in gases containing dust particles

Natalia Yu. Babaeva[1], Ananth N. Bhoj[2] and Mark J. Kushner[1]

[1]Iowa State University, Department of Electrical and Computer Engineering, Ames, IA 50011 USA
(natalie5@iastate.edu, mjk@iastate.edu)
[2]University of Illinois, Department of Chemical and Biomolecular Engineering, Urbana, IL 61801 USA
(bhoj@uiuc.edu)

Atmospheric pressure plasmas, and streamers in particular, sustained air often encounter dust or aerosol particles. The dynamics of streamers intersecting such particles are of interest due to their possible use for functionalizing the surfaces of particles. Using a 2-dimensional plasma hydrodynamics model with unstructured meshes, the consequences of dust particles on streamer dynamics was investigated while varying the particle sizes. We found that while small dielectric particles are enveloped by the streamer, larger particles can intercept and reinitiate streamers.

1. Introduction

The propagation of streamers in atmospheric pressure gases is of interest in plasma remediation of toxic gases, ozone production and functionalization of surfaces. The air (or other gases) in these non-pristine environments is often contaminated with particles or aerosols having sizes of 10s to 100s μm. These particles can be generated within the plasma by nucleation, injected externally into the plasma, or occur naturally (such as aerosols). The purposeful functionalization of the surface of small particles for industrial and pharmaceutical purposes is also of interest. The particles may have varying degrees of conductivity, from metallic to classically dielectric. The intersection of propagating streamers with particles not only results in charging of the particles but can also significantly perturb the streamer dynamics due to loss of charge, electric field enhancement and secondary processes. For certain conditions these perturbations can result in streamer branching [1]. In this paper, we report on results from a computational investigation of the intersection of a positive corona streamer sustained in humid atmospheric pressure air with dielectric particles.

2. Description of the model

The model used in this investigation is a variant of nonPDPSIM, described in Ref. [2]. The fundamental equations for charged species that are solved are

$$-\nabla \cdot \varepsilon \nabla \Phi = \sum_j N_j q_j + \rho_s \,, \qquad (1)$$

$$\frac{\partial N_j}{\partial t} = -\nabla \cdot \vec{\phi}_j + S_j \,, \qquad (2)$$

$$\frac{\partial \rho_s}{\partial t} = \sum_j -\nabla \cdot q_j (\vec{\phi}_j + S_j)) - \nabla \cdot (\sigma(-\nabla \Phi)) \,, \qquad (3)$$

where ε, Φ, ρ_s, N, ϕ, σ, S, q are the permittivity, electric potential, surface charge density, species number density, species flux, conductivity of solid materials, source term and elementary charge respectively. Poisson's equation (1), transport equations for conservation of the charged species j (2) and the surface charge balance equation (3) are simultaneously solved using a Newton iteration technique. The source term includes photoionization which accounts for the production of precursor electrons ahead of the streamer front. Photoemission produced by fluxes of photons incident on the surface of dust particles is also included in the model. The trajectories of the emitted photoelectrons are followed with the Electron Monte Carlo Module (EMCM). Transport equations for neutral species are solved following an update of the charged species using time slicing techniques. The species included in the model are: N_2, $N_2(v)$, N_2^*, N_2^{**}, N_2^+, N, N*, N^+, N_4^+, O_2, O_2^*, O_2^+, O_2^-, O^-, O, O*, O^+, O_3, H_2O, H_2O^+, H_2, H, OH and e. The 2-dimensional unstructured mesh is produced with the commercial mesh generator Skymesh2.

3. Effect of dust particles on streamer dynamics

The model geometry is shown in Fig. 1. The positive corona discharge is sustained between a rod with radius of curvature of 0.07 cm, charged to 15 kV, and a flat grounded surface separated by 0.2 cm. The gas mixture is $N_2/O_2/H_2O$ = 79.5/19.5/1.

The process of streamer–particle interaction includes two stages. During the first stage, the streamer front approaches the particle. A strong interaction occurs between the electric field at the streamer tip and the enhanced local field near the poles of the particle. The second stage is more complex including the processes of particle charging when the positive charge of the streamer tip is delivered to the particle surface, emission of secondary electrons from the surface and formation of an electron wake due to electron flow around the particle.

3.1. Streamer parameters before the streamer front interacts with the dust particle

Three cases are used to illustrate the influence of dielectric particles of different sizes on the streamer dynamics. The first is streamer propagation without particles, conditions that have been previously investigated in 1- and 2-dimensions [3]. In the second case, a small dielectric particle with a radius of 20 μm (relative dielectric permittivity 20) was located on the axis 0.11 cm below the powered electrode. In the third case, the particle was replaced by a larger grain (radius 70 μm) of the same material. The distributions of the reduced electric field 9.6 ns after a voltage pulse was applied to the upper electrode are shown in Fig. 1.

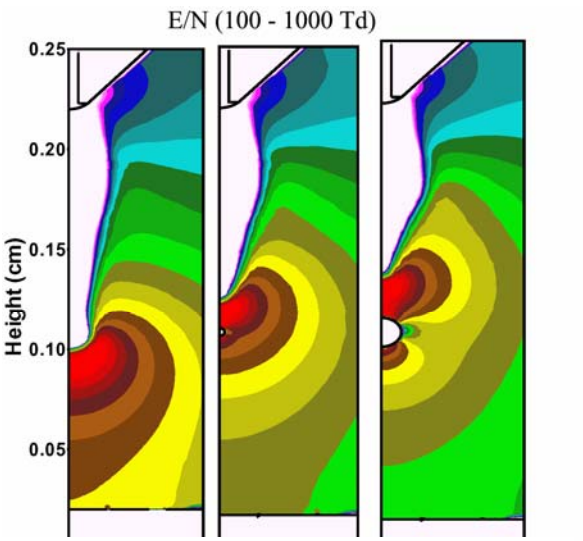

Figure 1. The magnitude of the reduced electric field E/N (log scale, Td) for a streamer at t = 9.6 ns (left) Without a dust particle, (middle) interaction with a dust particle of radius 20μm and (right) interaction with a dust particle of radius 70 μm.

The interaction of the streamer with the dust particle produces two important effects. First, the streamer velocity decreases when approaching the particle. Second, the blunt conical shape of the streamer front develops into a sharp cone as the streamer approaches the region of the enhanced electric field near the particle. Typically, the electric field around a spherical body placed in an external field is enhanced near the poles (for the given geometry and the direction of the electric field) and is small on the particle equator. The closer the streamer tip approaches the particle the more intense is the field enhancement near the particle. The larger electric field feeds back through elevated electron temperatures. In this particular case, the charging of the particle as the streamer approaches intensifies the effect. The mutual electrodynamic interaction between the streamer field and the local field near the dust grain is one of the primary mechanisms of streamer-particle interaction.

3.2. Streamer parameters after the streamer front arrives at the particle

Development of the streamer front and other parameters are shown in Figs. 2-5 as the streamer front arrives at the large particle.

When approaching the dust grain the streamer front undergoes further perturbations. The conical shape of the streamer head develops into a concave tip as shown in Fig. 2. The streamer body squeezes the region of enhanced electric field between its tip and the particle surface which faces the streamer front. The electric field and, as a consequence, the rate of electron impact ionization attains high values near the particle surface (Fig. 3). As a result, a new streamer starts from the bottom side of the particle which faces the grounded electrode. To some degree, the particle is acting like a capacitor which requires time to charge, thereby slowing the streamer but after charging provides a convenient source of voltage to launch the second streamer.

Following launching of the second streamer, the plasma of the first streamer envelopes the dust particle and, finally, converges with the second streamer. This results in a wake of smaller electron density above the particle due to electron flow around the particle, as shown in Fig. 4.

The first streamer delivers a substantial positive charge to the upper side of the particle which faces the streamer front (Fig. 5). The process of charge deposition as the streamer tip passes is rapid, occurring within 1 ns. The subsequent process of charge accumulation (or dissipation) occurs on a much longer time scale. As such, in a repetitively pulsed system, the charge accumulated on a dust particle can influence the streamers of the following pulses. Although the main features of streamer interaction with the smaller particle for the given conditions are similar, there is a dependence on size, as well as dielectric constant and conductivity.

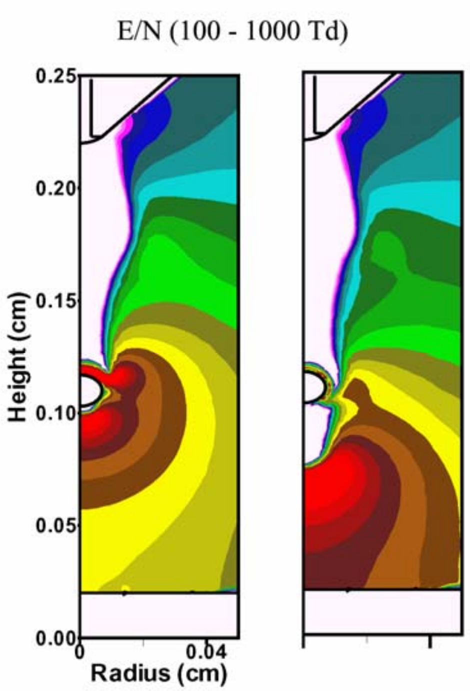

Figure 2. The magnitude of the reduced electric field E/N (log scale, Td) as the streamer front arrives at the 70 μm particle at (left) t = 11 ns and (right) t = 12 ns.

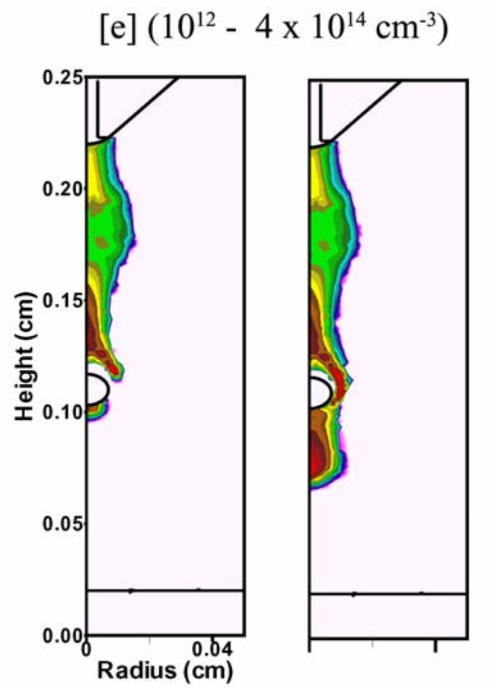

Figure 4. Electron density (log scale, cm^{-3}) as the streamer front arrives at the 70 μm particle at (left) t = 11 ns and (right) t = 12 ns.

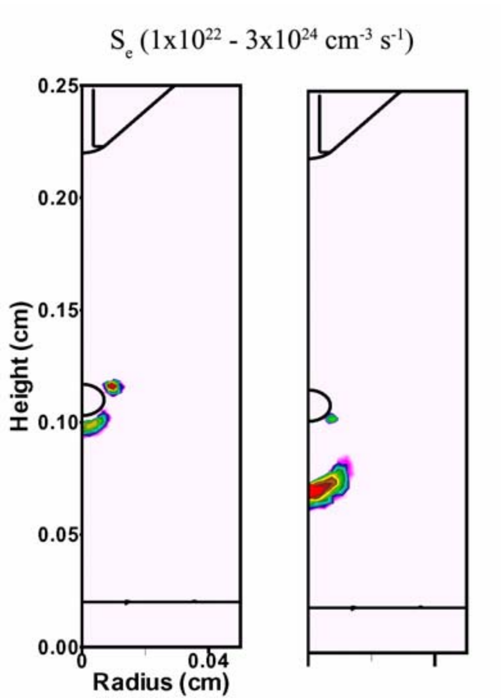

Figure 3. Electron impact ionization source (cm^{-3} s^{-1} log scale) as the streamer front arrives at the 70 μm particle at (left) t = 11 ns and (right) t = 12 ns.

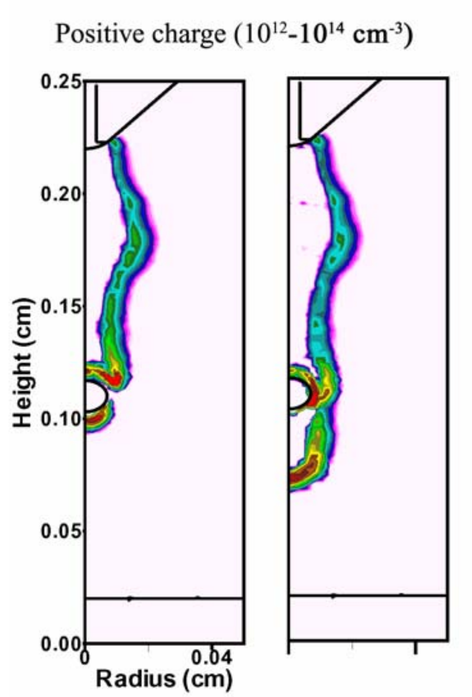

Figure 5. The positive charge density (log scale, cm^{-3}) as the streamer front arrives at the 70 μm particle at (left) t = 11 ns and (right) t = 12 ns

3.3. Streamer interaction with multiple Particles

The consequences of random and ordered collections of dust particles were also investigated while varying the particle sizes and polarity of the applied voltage (e.g., positive and negative streamers).

As an example, results for a positive streamer interacting with two dust particles (70 µm radius) aligned on the axis are shown in Fig. 6. The initial stage of interaction with the streamer for the upper particle is similar to that described for a single isolated particle. As with the isolated particle, a second streamer is launched from the bottom of the first particle. This second streamer then compresses the electric field between the tip of the second streamer and the surface of the second particle. As the second particle charges, a third streamer is launched from it lower surface. This process is very much like a relay in which the streamer is handed off between particles. There is electric field enhancement at the upper pole of the particle, particle charging, electric field enhancement at the lower pole and launching of the daughter streamer. This process is nicely repetitive for particles that are of the same size and evenly spaced as in this example. The process is more complex for more random assemblies of particles having different sizes.

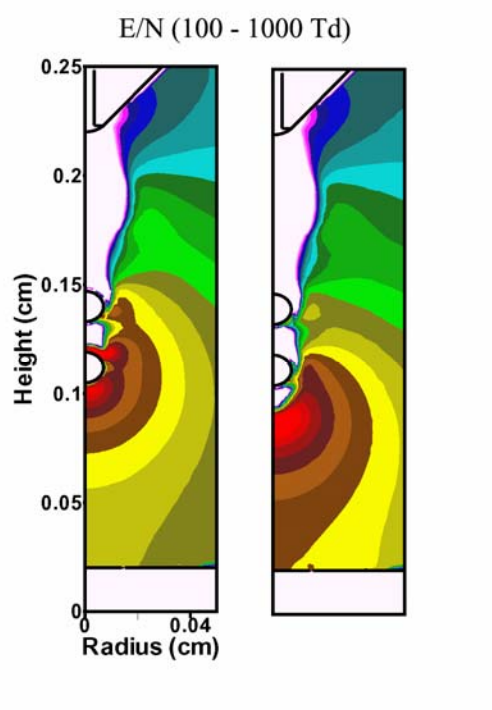

Figure 6. The magnitude of the reduced electric field E/N (log scale, Td) as the streamer arrives at two 70 µm particles at (left) t = 8.4 ns and (right) t = 9.4 ns.

4. Acknowledgement

Work was supported by the National Science Foundation (CTS03-15353) and Air Force Research Laboratory.

5. References

[1] T. M. Briels, E.M. van Veldhuizen and U. Ebert, IEEE Trans. Plasma Sci. **33**, 264 (2005)
[2] A. N. Bhoj and M. J. Kushner, J. Phys. D. **37**, 2910 (2004)
[3] N. Yu. Babaeva and G. V. Naidis, IEEE Trans. Plasma Sci. **25**, 375 (1997)