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Plasmas in Small Spaces

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With the advent of plasma display panels and microdischarges, there is great interest in sustaining plasmas in small spaces. In principle, plasmas in small spaces should scale in the same manner as plasmas in macroscopic spaces by keeping pd (pressure × dimension) constant. In practice, this is not necessarily the case. In many instances the characteristic size of the plasma is on the order of the Debye length and the surface-to-volume ratio is sufficiently large that surface processes dominate. Following pd scaling also implies that higher pressures are required to facilitate plasmas in small spaces. The high pressure and small dimensions also imply that transients are particularly important. In this paper, the dynamics of plasmas sustained in small spaces will be discussed.

1. Introduction

Sustaining plasmas in small spaces has received renewed interest due to the use of small scale plasmas in display panels and the use of microdischarges for a variety of applications from photon to radical sources.[1] In principle, "small" plasma devices can be designed by following pd (pressure × characteristic dimension) scaling. In practice, this scaling may not hold. By "small" we refer to high pressure plasmas in which the Debye length, λ_D, and characteristic dimension are commensurate; or the surface-to-volume ratio is sufficiently large that surface processes dominate the kinetics. The former requirement implies that the partially ionized gas does not necessarily need to be a plasma since quasi-neutrality is not mandatory on such small scales. The latter requirement implies that the interaction of the plasma with the surface may determine bulk plasma properties.

Although small plasmas are technologically a fairly recent development, small plasmas have been studied in many contexts.[2] For example, dielectric-barrier-discharges (DBDs) and corona discharges may qualify as being small plasmas since in some cases λ_D can be commensurate with streamer widths and plasma surface interactions can dominate their behavior. This is particular interesting in transient plasmas where the dynamics of charging can be important.

In this paper, the dynamics of atmospheric pressure streamers with "small" structures will be discussed. These are intrinsically transient processes due not only to the transient nature of the streamer but also to the rapid charging of surfaces and large electric fields that impinge on the structures. This discussion will be facilitated by results from a 2-dimensional plasma hydrodynamics model. We will find that the transient dynamics of streamers in and around small spaces is very sensitive to surface processes.

2. Description of the model

The model used in this investigation is a variant of nonPDPSIM, described in Ref. 3. The fundamental equations for charged species 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. In addition to collisions, the source terms include secondary electron emission, photoionization in the bulk and photoemission from surfaces. The trajectories of the emitted electrons from surfaces are followed with an electron Monte Carlo simulation. Transport equations for neutral species are solved following an update of the charged species using time slicing techniques. The bulk flow of gases is addressed by solving a modified form of the Navier Stokes equations.

$$\frac{\partial\rho}{\partial t}=-\nabla\cdot\rho\vec{v}\,, \qquad (3)$$

$$\frac{\partial \rho \vec{v}}{\partial t} = -\nabla P - \nabla \cdot \rho \vec{v} \vec{v}_i - \nabla \cdot \overline{\overline{\tau}} + \sum_i q_i N_i \vec{E}\,, \tag{4}$$

$$\frac{\partial \rho c_p T}{\partial t} = -\nabla \cdot \left(-\kappa \nabla T + \vec{v} c_p T \right) - P\left(\nabla \cdot \vec{v} \right) + \left(\overline{\overline{\tau}} \cdot \nabla \vec{v} \right) - \sum_i \Delta h_i S_i + \sum_i \vec{j}_i \cdot \vec{E} \tag{5}$$

where ρ is the total mass density (including charged species), T is the gas temperature, P is the thermodynamic pressure (ideal gas behavior), $\overline{\overline{\tau}}$ is the viscosity tensor, κ is the thermal conductivity, c_p is the heat capacity, and Δh_i is the heat of formation for reaction i having source function S_i.

3. Plasmas Penetrating into Small Spaces

The use of atmospheric pressure plasmas to modify the surface properties of material is a common industrial process that is being investigated to create higher value material. For example, humid air plasmas are used to functionalize the surfaces of hydrocarbon polymers, such as polypropylene, to increase their surface energy to increase their wetability.[4] This is accomplished by creating oxygen radicals that affix on the surface. Often these materials have non-planar surfaces or purposely have textured surfaces, such as for use as scaffolding for tissue engineering.

The quality of the material produced by functionalization by air plasmas is in part determined by how well those plasmas can penetrate into the small structures on the surface. For example, a humid air negative corona plasma (1 atm, $N_2/O_2/H_2O$ = 79.5/19.5/1, -15 kV) is sustained across a 2 mm gap, as shown in Fig. 1. The geometry is symmetric across the centre line. The grounded substrate is covered by a polypropylene sheet making the corona operate as a DBD. The surface of the polypropylene has microstructure with characteristic dimensions of about 1 µm, as might be fabricated for a scaffold for cell adhesion. (The computational mesh and transport algorithms have sufficient dynamic range to resolve all of these spatial lengths.)

The electron density after the avalanche has reached the polymer sheet and started to spread due to surface charging is shown in Fig. 1. The peak electron density is 1.6 x 10^{13} cm^{-3}. The degree and dynamics of plasma penetration into the surface features is in large part governed by rapid charging of the surface, as shown in Fig. 2. As the electron density approaches the surface, the features that have large view angles to the plasma charge most rapidly. This creates an opposing electric field which inhibits the ability of the plasma to penetrate into the deep crevices. The local rate of charging is determined by the topography of the microstructure and the current density from the plasma. The plasma "bounces" off the surface as a sheath is produced when the capacitance of the surface structures is fully charged. This is a rapid and dynamic process.

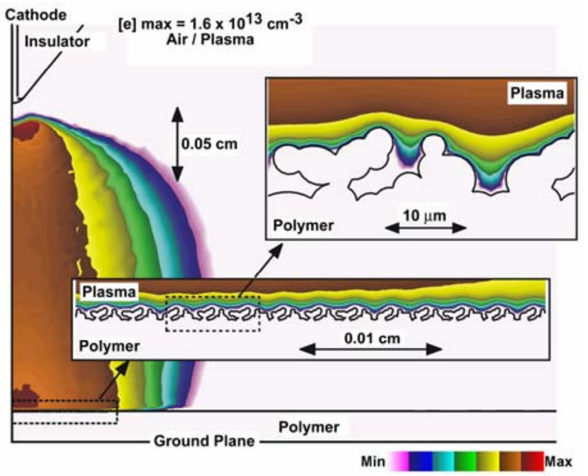

Figure 1 – Geometry for the negative corona treatment of polypropylene using a humid air negative corona plasma. The gap is 2 mm. The polymer sheet has micron-sized structure. The electron density (2-decade log scale) is shown after the plasma begins to spread on the dielectric.

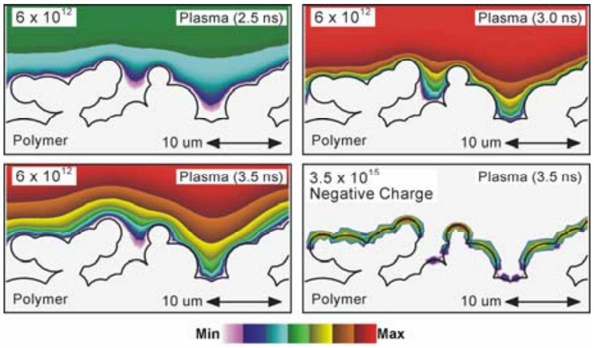

Figure 2 – Electron density as the plasma approaches the polymer sheet. The penetration of the electrons into the polymer topography is largely governed by the charging of surface features. The charging is largest for features with large view angles to the plasma.

4. Streamers colliding with small particles

Corona discharges sustained in air often intersect small particles (e.g., dust, aerosols). The rapid dynamics of charging of small structures on surfaces by corona streamers discussed above is an important consideration when streamers intersect with similarly small particles. The amount of charge that is removed from the streamer to charge dielectric particles to the plasma potential is sometimes sufficient to change the dynamics of the streamer.

For example, the intersection of a positive corona (+15 kV) sustained in humid air with three dielectric particles (radius 60 μm) is shown in Fig. 3. The geometry is otherwise the same as in Fig. 1 except that the lower surface is all metal. The electron density and E/N around the particles as the streamer passes are shown. As the electron avalanche approaches a particle from the top, the streamer stalls as the plasma charges the particle. At this time, the E/N is greatly intensified at the top surface of the particle. This is partly due to the compression of voltage in front of the conductive streamer.

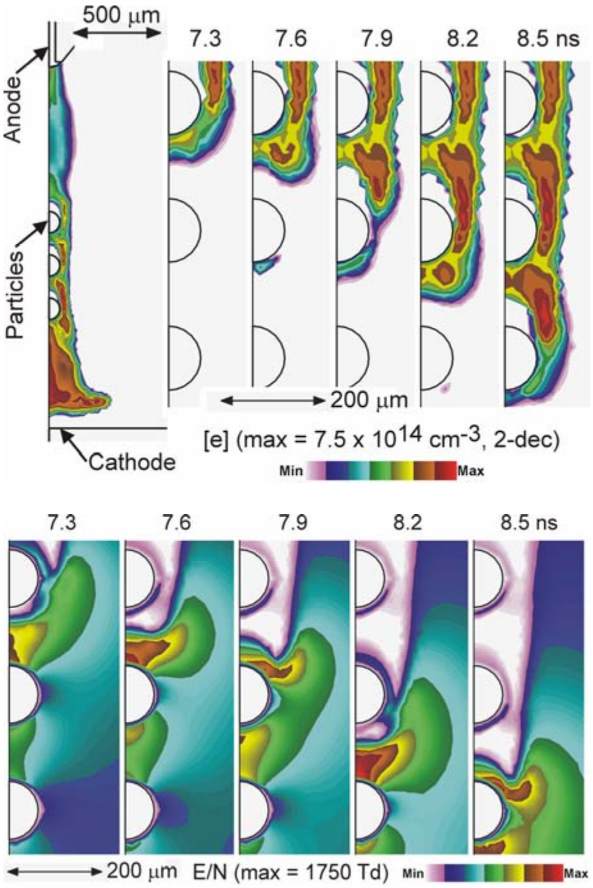

Figure 3 – The intersection of a positive corona sustained in humid air with 3 dielectric particles. (top) Electron density when as the stream spreads on the cathode and the electron density intersecting the particles at different times. (bottom) E/N around the particles at the same times.

As the particle charges and acquires the plasma potential, the E/N decreases on top of the particle while increasing at the bottom. The plasma envelopes the particle, a streamer is launched from the bottom of the particle and the process is repeated. Note that there is a wake above the particles on their cathode side. The wake is devoid of electrons that are drifting towards the of the reactor.

5. Streamers penetrating through small structures.

The ability to cheaply functionalize the surfaces of parts with complex shapes will depend on the ability of atmospheric pressure plasmas to penetrate through small spaces. The difficulty of achieving such penetration is demonstrated by the passage of a negative corona sustained in humid air through 30 μm wide grooves in a plastic disk. The geometry for this case is shown in Fig. 4 where the electron density when the plasma has reached the lower surface is also shown. (The geometry is otherwise the same as in Fig. 1.) The electron density at various times as the plasma attempts to penetrate through the grooves is shown in Fig. 5.

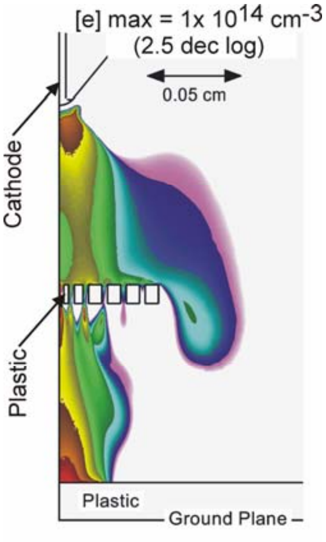

Figure 4 – Geometry of a negative corona streamer sustained in humid air penetrating through a grooved plastic disc. The electron density is shown when the streamer intersects the lower plastic plane

As the avalanche front approaches the disk, the propagation speed slows as the disk charges. The plasma penetrates only slowly through the grooves of the disk as significant charge is removed from the streamer to charge the inner walls of the structure. These grooves have very large surface-to-volume ratios. As the plasma emerges through the grooves, new small streamers are initiated by electric field enhancement at the opening of the grooves. These new streamers merge further downstream.

Note that the plasma is unable to penetrate through the outer grooves where the bulk plasma density is lower. This is due, in part, to the smaller current density available at the outer radius to charge the dielectric. As the plasma attempts to penetrate through the grooves it is essentially extinguished. The plasma then seeks a lower impedance path towards the anode. This lower impedance path is around the disk in spite of the path length being longer.

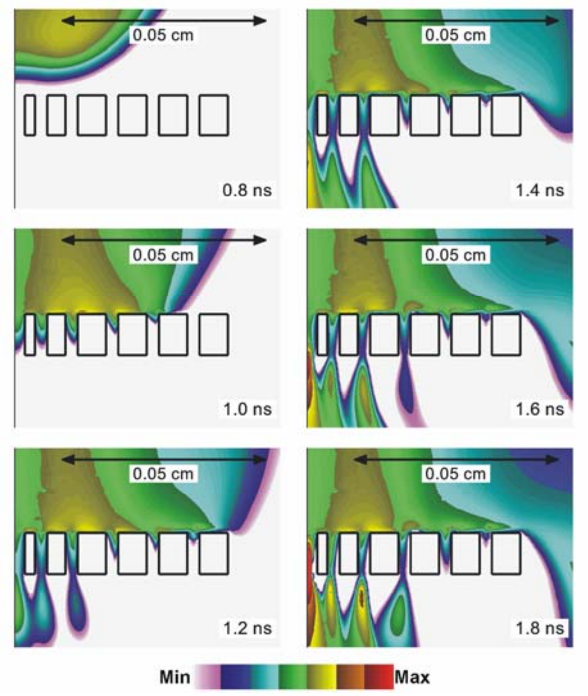

Figure 5 – The intersection of a negative corona sustained in humid air with a grooved plastic disk for the geometry shown in Fig. 4. The electron density is shown at different times. The maximum electron density is 6 x 10^{14} cm^{-3}.

6. Concluding Remarks

The success of using atmospheric pressure plasmas, and coronas in particular, to functionalize the surfaces of high value materials will depend on how uniformly the surface can be processed. One important aspect of this process is how the plasma behaves in and around small spaces. The interaction of these transient plasmas, and streamers in particular, with small spaces is acutely affected by the dynamics of charging of the surfaces. Removal of charge from the streamer to charge these surface can significantly affect the dynamics of the streamer. The streamer will, in general, seek the lowest impedance path. This may result in plasmas not penetrating into small spaces that have high impedances.

7. Acknowledgement

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8. References

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