Miniature, 3D-Printed, Monolithic Arrays of Corona Ionizers

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Abstract. We report the design, fabrication, and characterization of the first 3D-printed, monolithic corona ionizer arrays (CIAs) in the literature. The CIAs are binder inkjet-printed in stainless steel 316L and have 5, 9, or 32 emitters (emitter pitch equal to 6 mm, 4 mm, or 2 mm, respectively); each emitter is 5 mm tall, with 1.7 mm diameter at the base and 300 μm diameter at the tip. Current-voltage data were collected in air with the emitter array biased negatively with respect to a counter-electrode for varying inter-electrode separation; the current divided by the bias voltage has a linear dependence with respect to the bias voltage minus the onset voltage – in agreement with the Townsend current-voltage law. 3D finite element simulation of the electrostatics of the densest CIA using the COMSOL Multiphysics evidences that the emitters at the periphery of the array have the highest electrical field, while a 1D electrohydrodynamic model implemented in the same software predicts a 400 μm-thick corona region surrounding the corona tip.

1. Introduction

A corona discharge is a high-electric field ionization phenomenon caused by the development of a self-sustained electron avalanche between a sharp electrode, i.e., corona electrode (typically a needle or a wire) and a blunt electrode, i.e., collector electrode (e.g., a flat plate or a cylindrical ring concentric to the corona electrode), with the high-curvature electrode intensifying the local electric field above the onset field of the working fluid; the ions create a plasma region around the corona electrode, which in their travel to the opposite electrode transfer momentum to the surrounding fluid. Compared to pumps with moving parts, corona pumps respond faster and produce significantly less noise [1], drawing great interest in developing applications such as air propulsion [2] and electronics cooling [3]. Decreasing the tip diameter and increasing the aspect-ratio of a corona ionizer yields devices that produce more ions for a given bias voltage and that activate with less voltage; in addition, ionization throughput can be increased via tip multiplexing. There are reports of MEMS corona ionizer arrays (CIAs) with average tip diameter as small as 25 μm and onset voltage as small as 1.25 kV, emitting currents as high as 16 μA [4]. However, these devices are unideal because they are pick-and-place assembled from planar microfabricated components to create a 3D structure, and they are made of soft materials, e.g., copper, which poses reliability problems.

Corona ionizers can operate on either polarity. However, negative corona ionizers (i.e., when the corona electrode is biased at a lower potential than the collector electrode) are more attractive for...
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2. Electrohydrodynamic model
We developed a model of the corona discharge dynamics to provide insight into the structure of the inter-electrode gap during operation of the corona ionizer. The simulation only considers one emitter in the array, and to simplify the simulation geometry, a 1D coaxial cylinder model was built where \( r_0 \) is the radius of the inner cylinder (the radius of the corona tip, i.e., 0.15 mm) and \( R \) is the radius of the outer cylinder, with \( R - r_0 \) equal to one of the air gap distances used in the experiments (7.947 mm, see Section 3). The outer electrode is grounded, while the inner electrode is biased at a negative DC voltage ramped by a hyperbolic tangent function. The dynamics of the gas-discharge model is governed by the continuity equations for the charged and excited particles

\[
\frac{dN_k}{dt} + \nabla \cdot \Gamma_k = S_k
\]

where \( N_k \), \( \Gamma_k \), and \( S_k \) are the number density, flux, and the volume source term of the species \( k \), respectively. In this model, four species, i.e., electrons, positive ions, negative ions and background gas neutrals, are considered and are indicated with subscripts \( e, p, n, g \), respectively. For each species, the flux is calculated with the drift-diffusion approximation

\[
\Gamma_k = s g m(q_k)N_k \mu_k E - D_k \nabla N_k
\]

where \( E \) the electric field and \( q_k, \mu_k \), and \( D_k \) are the charge, particle mobility, and diffusion coefficient of the species \( k \), respectively. The first term of the flux comes from the drift under the applied electric field, and the second term is diffusion-driven by the number density gradient. The electric field is obtained by solving the Poisson’s equation considering the distortion induced by the space charge accumulation in an inter-electrode space, in other words

\[
\epsilon \nabla \cdot E = \sum_k q_k N_k \phi \quad E = -\nabla \phi
\]

where \( \phi \) is the electric potential and \( \epsilon \) is the electrical permittivity of air. The source terms \( S_k \) are determined by the reactions occurring in the discharge volume; only the main phenomena in corona discharge are considered, i.e., the electron impact ionization, electron attachment, electron-ion recombination, and ion-ion recombination with rate coefficients for each process denoted as \( \alpha, \eta, \beta_{ep}, \) and \( \beta_{pn} \). Consequently, the source terms for each species are written as

\[
S_e = \alpha N_e|w_e| - \eta N_e|w_e| - \beta_{ep} N_e N_p
\]

\[
S_p = \alpha N_e|w_e| - \beta_{ep} N_e N_p - \beta_{pn} N_p N_n
\]
The discharge current \( I \) through the gas between electrodes is usually one of the main parameters of interest given that it can be easily measured in experiments. \( I \) can be calculated by the Sato's equation \([14]\):

\[
I = \frac{|q_e|}{\eta_e} \int_V \left( N_p w_p - N_n w_n - N_e w_e - D_p \nabla N_p + D_n \nabla N_n + D_k \nabla N_k \right) \cdot E_L \, dV + \frac{e}{\eta_a} \int_V \frac{\partial E}{\partial t} \cdot E_L \, dV \tag{7}
\]

where \(|q_e|\) is the magnitude of the electron charge, \(U_a\) is the applied bias voltage, and \(E_L\) is the space-charge free component of the electric field, i.e., the solution of equation (3) when the charge \(q_0\) is zero. The first term is a conductive component caused by the drift and diffusion of charged particles in the electrode gap; the second term is a capacitive current that only exists when the applied voltage is time-dependent.

The reduced ionization, \(\alpha/N_g\), and attachment, \(\beta/N_g\), coefficients are defined as functions of the reduced electric field \(E_k/N_g\) (local field approximation) and provided in look-up tables, and electron-positive ion, positive-negative ion recombination rates are approximated by constant parameters, which are pressure, \(P_g\), and temperature, \(T_g\), dependent. The Einstein relation between mobility and diffusion coefficients, \(D_e = \mu_e k_B T_e/q_e\), is valid with \(T_e\) the kinetic temperature and \(k_B\) Boltzmann’s constant. Mobility of heavy species is assumed to be constant, while for electrons look-up tables of drift velocity, \(\mu_e E\), and characteristic energy, \(D_e/\mu_e\), are used to calculate mobility and diffusion coefficients; in the model, the data are adopted from published references for dry air at room temperature and at atmospheric pressure (i.e., \(P_g = 1 \text{ atm, } T_g = 293 \text{ K}\))[15],[16]. In a negative corona discharge, additional production of electrons occurs at the corona tip due to the positive ions bombarding its surface. The electron generation fraction is denoted by the secondary ionization coefficient \(\gamma\), which heavily depends on the electrode’s material and roughness –here 0.001 is used. Because secondary electron emission only occurs at the tip surface, it was not included in the volume source term.

The current, \(I\), collected at the anode for different DC bias voltages is shown in figure 1, which is slightly deviated from Townsend’s linear current-voltage law. The onset voltage, \(U_{a0}\), is estimated from the simulation as 5.849 kV, which is close to the theoretical value: Peek’s formula \((E_0 = 3.1 \times 10^6 \delta (1 + 0.308/\sqrt{\delta T_0})\), where \(\delta\) is the relative density, \(T_0 P_0/T_g P_0\), where \(P_0\) and \(T_0\) are the reference pressure and temperature, respectively; \(P_g = 1 \text{ atm, } T_g = 293 \text{ K}\)) predicts a critical electrical field equal to 1.089\times10^7 \text{ V/m}; for coaxial cylinders, the corresponding voltage ( \(U_{a0,ckt} =\) 

- Figure 1. Predicted current over bias voltage versus bias voltage; \(m\) is the slope of the least-squares linear fitting.
- Figure 2. Time evolution of the number density of electrons (dash-dotted), negative ions (solid) and positive ions (dashed) during ramp up of the bias voltage to -11kV.
$E_{ad} r_0 \ln (R/r_0)$ is 6.416 kV. Figure 2 shows how the number density of electrons and heavy species change during the transient of increasing the bias voltage from 0 to -11 kV. The simulations predict that the high-density positive ions are confined near the corona tip, where the electrical field is high; negative ions propagate to the anode, forming a negative cloud spanning the whole air gap with a relatively stable density. Also, the rise in negative ions and electrons overlaps the sharp drop of positive ions, which is the corona region (around 400 μm in these simulations); the edge of the corona zone has a reduced electric field of 155 Td, close to the theoretical value of 130 Td at which ionization balances attachment.

3. Experimental characterization

The 3D printed CIAs have 5 mm-tall tips with 1.7 mm diameter at their base and 300μm tip diameter at their top; devices with 5, 9, and 32 emitters (tip pitch equal to 6 mm, 4 mm, and 2 mm, respectively) were characterized in air at atmospheric pressure and at room temperature. A 32-tip emitter is shown in figure 3. Metrology shows that the average diameter of the tip is 283.37±6.49 μm, with average areal surface roughness equal to 4.627 ± 1.829 μm.

CIAs with different number of emitters were tested in the negative polarity using as collector electrode a 100 μm-thick perforated metal grid with 5.5 mm, 3.5 mm, or 1.5 mm diameter apertures (for the 6 mm, 4 mm, and 2 mm emitter pitch devices, respectively); each aperture is concentric to the an emitter tip. Images of the setup taken during the experiment and of the collector electrodes taken after the experiments show that the internal tips of the CIAs were significantly less active/didn’t generate any

Figure 3. (a) Field view and (b) tip close-up of a 32-tip CIA printed in SS 316L via inkjet binder printing.

Figure 4. YZ-plane cuts @ X = (a) -5 mm, (b) -3 mm, and (c) -1 mm of the electrostatic solution of a 32-tip CIA biased at -11kV. Color scale is in V/m.

Figure 5. $I/U_a$ vs. $(U_a - U_{a0})$ characteristics for (a) 5-emitter, (b) 9-emitter, and (c) 32-emitter 3D-printed CDIs. Red, green, blue, and magenta curves correspond to electrode separations equal to 7.95 mm, 11.12 mm, 14.30 mm, and 17.47 mm, respectively; the $m$ value quoted for each case is the slope of the least-squares fitting.
corona discharge. This can be explained by the shielding effect in which the electrostatic field at the tips on the edge of the array is significantly higher than that at the central tips (figure 4—in the figure, the plane X = 0 passes at the center of the device). The shielding effect is stronger for smaller tip separation (i.e., devices with more tips).

The total corona current collected at the anode, \( I \), for each applied voltage \( U_a \) was recorded while varying the gap between the electrodes; each device will start generating current at a bias voltage equal to \( U_{a0} \). The \( I/U_a \) vs. \( (U_a - U_{a0}) \) curves show excellent agreement with the Townsend’s current-voltage law (figure 5). The corona current decreases if the inter-electrode gap is increased due to the decrease of the electric field on the tips; however, a smaller gap spacing can easily lead to arcing. Devices with different number of tips tend to generate the same total corona current at the same \( (U_a - U_{a0}) \) bias voltage, although more tips are set to discharge as the number of tips increases. This can be ascribed to the stronger interference between adjacent tips when the tip-to-tip spacing decreases.

4. Conclusion
We reported the first miniaturized, 3D-printed, monolithic multi-emitter corona discharge ionizers in the literature. A 1D hydrodynamic drift-diffusion model of the corona discharge in dry air at atmospheric pressure and room temperature was built considering the generation, movement, and loss of electrons, positive ions, and negative ions in the interelectrode gap while considering ionization, attachment, and recombination processes. The model predicts a ~400 \( \mu \)m-thick corona region surrounding the corona tips. Electrical characterization of CIAs of different number of tips and with different inter-electrode separation show that the devices follow Townsend’s current-voltage law. The maximum measured total currents is equal to 422 \( \mu \)A (13.2 \( \mu \)A average per-tip current, i.e., a three-fold larger than reported MEMS devices with similar number of tips [4]). Optimization of the CIA design should be conducted to ensure that all the emitters are activated to increase the efficiency of the devices.

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