Charging of Surfaces with a Wire Corona Discharge: Simulations of Plasma Hydrodynamics with Moving Surfaces

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Abstract

Atmospheric pressure corona electric discharges are important components of electrophotographic (EP) printing technologies for charging surfaces and photoconductors. A typical corona discharge consists of a wire biased with dc potential of 100's V plus a few kV of ac bias. An electric discharge is produced around the corona wire from which electrons drift along the applied electric field to charge the underlying surface. This reduces the voltage drop across the gap which then terminates the discharge. In printing this underlying surface is continuously moving during charging. As a result, the corona discharge is re-ignited by the increased voltage drop provided by the incoming uncharged surface. To aid in development of these devices, an investigation based on first principles, multi-dimensional computer modeling has been conducted. We found that the uniformity of the summation of these charging cycles is sensitive to the conductivity, dielectric constant and speed of the moving surface, and the voltage waveform. Parametric results for charging of surfaces while varying these parameters will be discussed.

Introduction

In many electrophotographic (EP) printing technologies, a corona electric discharge sustained in room air is used for charging the surface of a photoconductive element [1]. Although corona discharges do have challenges (e.g., large power source, ozone generation), the simplicity and low cost of these devices have motivated continued research into optimizing their performance.

In a typical corona discharge charging process, a wire is biased to 100s V dc plus a few kV of ac voltage. The wire is separated from the photoconductor (PC) by gaps of tens of microns to a mm. The dielectric PC is typically in contact with a ground plane. A large electric field is produced around the wire by geometric enhancement and the discharge is initialized when free electrons (often emitted from the wire) are accelerated by these strong electric fields to trigger an avalanche (or ionization wave). When the discharge is produced by a negatively biased wire, the net drift of electrons and negative ions is towards the underlying PC surface. The surface is then charged negatively, which reduces the electric field in the gap and may terminate the discharge. The plasma may also spread along the surface.

Corona discharges are used in at least two of the process steps of EP printing [2]. In the charging step, the PC surface is uniformly charged using a corona discharge produced in a device called a *corotron*. The corotron consists of a shielded wire intended to stabilize the operation but lower the charging efficiency. In the transfer step, a corotron is used to charge the back of the paper to optimize adhesion of toner particles. In a typical corona discharge, the charging of the surface removes potential from the gap between the corona wire and surface, thereby reducing the magnitude of the electric field. If the discharge is only sustained by dc (or quasi-dc in a pulsed mode) voltage, the plasma is then terminated by the underlying surface charges.

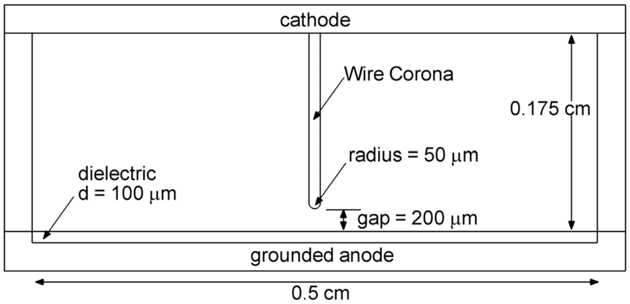

***Figure 1**. Schematic of the wire corona discharge used in the model.*

In this paper, we discuss results from a computational investigation of an idealized corona discharge and surface charging properties when the charged surface is stationary and moving. The modeling platform used in this investigation, *nonPDPSIM*, is a first principles, two-dimensional multi-fluid hydrodynamics simulation performed on an unstructured mesh [3]. *nonPDPSIM* solves transport equations for charged and neutral species, Poisson's equation for the electric potential and the electron energy conservation equation for the electron temperature. A Monte Carlo simulation is used to track sheath accelerated secondary electrons emitted from surfaces. A spatially fine Cartesian mesh is overlaid onto the unstructured mesh, electric field quantities and the electron impact source functions are computed and interpolated between the unstructured and structured mesh points. Rate coefficients and transport coefficients for the bulk plasma are obtained from local solutions of Boltzmann's equation for the electron energy distribution. Radiation transport is addressed using a Green's function.

Corona Discharge and Charging Process

To emphasize the plasma-surface interactions during charging, a simplified corona device has been modeled, as shown in Fig. 1. The device consists of a metal corona wire biased with negative dc voltage. The wire has a width of 100 μm and height of a few mm. The radius of the corona tip is 50 μm which is separated from an underlying dielectric sheet 100 μm thick, which represents the PC, by a 200 μm gap. The sheet has a relative permittivity of $\varepsilon_r = 5$. The PC is in contact with grounded electrode and is initially uncharged. The operating conditions are 1 atm of pure N_2 at 300 K.

The plasma properties of the corona discharge and charging process of the underlying dielectric PC surface will first be dis

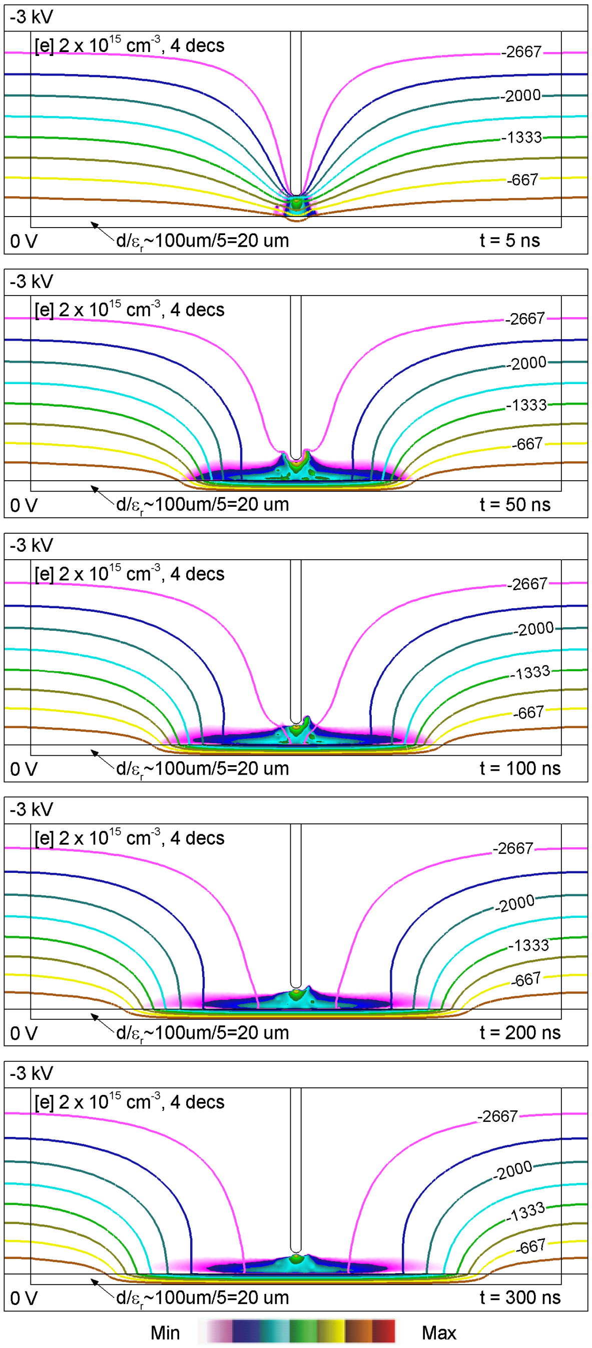

***Figure 2**. Time evolution of electron density (log scale, cm^{-3}) in a corona discharge sustained by a corona wire have a -3 kV dc bias. The electric potential is shown by the contour lines (labels are in volts).*

cussed when the surface is stationary. The wire and top cathode plate are biased to -3 kV.

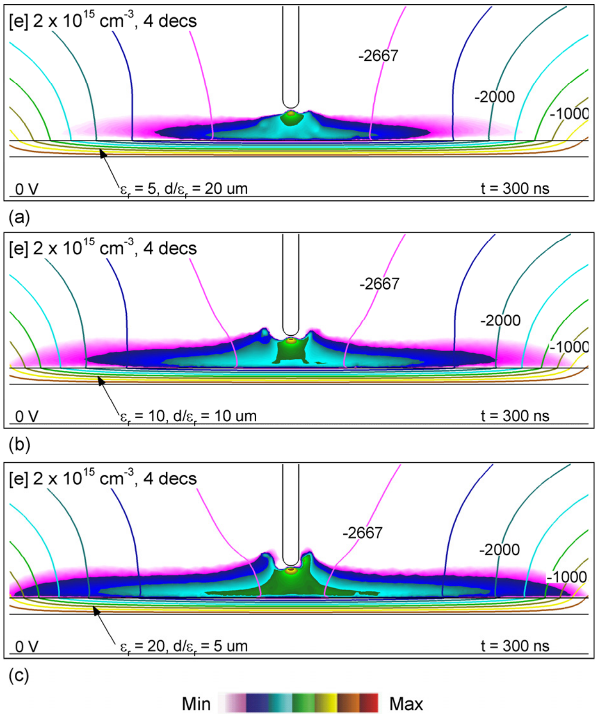

***Figure 3.** Electron density (log scale, cm^{-3}) in corona wire discharge spreading on the dielectric surface having relative permittivities of ε_r = (a) 5, (b) 10 and (c) 20. The electric potential is shown by the contour lines (labels are in volts).*

The time evolution of the electron density and electric potential in the corona discharge are shown in Fig. 2. Within a few nanoseconds, an electron avalanche occurs between the corona tip and dielectric surface due to the high potential gradient of 100 kV/cm. Electron densities up to 1.5×10^{14} cm^{-3} are generated at the corona tip at this initial stage (t = 5 ns in Fig. 2). Ionization is provided by two sources. The first is ionization by high energy electrons emitted from the wire by ion and photon secondary emission and accelerated in the large electric fields at the tip of the wire. The second is electron impact ionization by lower energy bulk electrons. The rates of ionization directly underneath the wire corona by these two sources are comparable, with values of 10^{22} - 10^{23} cm^{-3} s^{-1}. Electrons drift along the electric field to the underlying dielectric sheet and charge it negatively. As the plasma becomes conductive and charges are placed on the PC, the electric potential is shorted or shielded out. Electric potential lines are then trapped in the dielectric due to the negative charging of the surface.

As the discharge proceeds, the charging of the surface reduces the voltage drop between the corona and dielectric and hence largely decreases the electron impact ionization source from bulk plasma directly underneath the corona tip. However, electron ionization from secondary electrons in the corona sheath still occurs due to UV photons and positive ion bombardment onto the negatively biased corona wire. Secondary electrons continuously emitted from the corona are accelerated by the sheath potential and ionize the gas to provide an electron source up to 5×10^{22} cm^{-3} s^{-1}. At this stage, the corona discharge is sustained mainly by secondary electron ionization process.

Although voltage drop underneath the corona tip is reduced by surface charges, the conductive plasma does translate the potential of the cathode wire to the tip of the electron avalanche along the surface. As a result, there is still a large potential drop between the edge of plasma and the uncharged surface. A surface ionization wave is then triggered at the edge of the plasma and propagates outward until the voltage drop at the surface is insufficient to

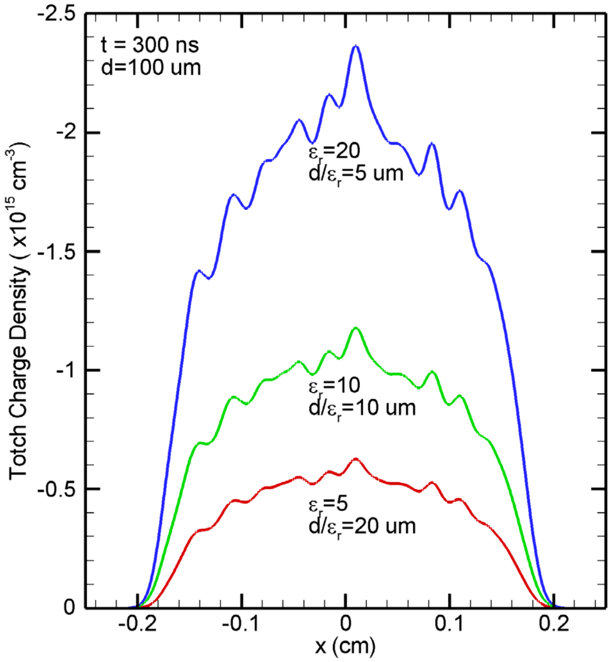

Figure 4. *Total charge density profile (cm^{-3}) on the dielectric surface with ε_r = 5, 10 and 20. The position of x=0 is directly underneath the corona tip.*

sustain the plasma. The spreading of the discharge on the surface is symmetric as there is uncharged dielectric on both sides of the wire, producing electric fields which avalanche electrons in both directions.

Surface Charging: Equivalent Electrical Dielectric Thickness

A corona discharge or dielectric barrier discharge (DBD) interacts with its electrodes and underlying dielectric in a circuit-like manner. The applied voltage is divided between the plasma column, avalanches front, sheath and underlying dielectric. The voltage drop in the dielectric is proportional to its equivalent electrical dielectric thickness, D=L/εr, (L = dielectric thickness and εr=dielectric constant). Manipulating the capacitance of the dielectric sheet could affect the sheath voltage, electron impact ionization rates and so spreading of the plasma along the surface. The electron density in a corona discharge for dielectric surfaces having εr = 5, 10, and 20 at t = 300 ns are shown in Fig. 3. Even before the discharge occurs, there is smaller voltage drop in the dielectric having larger εr, and so there is more voltage across the gap to produce more ionization. When the corona discharge is produced and the plasma strikes the surface, the potential is translated through the conductive plasma to the dielectric sheet and charges the surface. With increasing εr, the capacitance of the dielectric is larger, and so it takes a longer time to charge the dielectric sheet. As a result, a higher electron density is produced to charge the underlying dielectric to a higher charge density. The total charge density profiles on the dielectric surface for εr = 5, 10, and 20 at t = 300 ns are shown in Fig. 4. The noise in the charging is in part a result of the randomness of the Monte Carlo simulation used for secondary electrons. The peak total charge density linearly increases from 6 × 1015 cm-3 to 2.4 × 1016 cm-3 as the dielectric constant increases from 5 to 20.

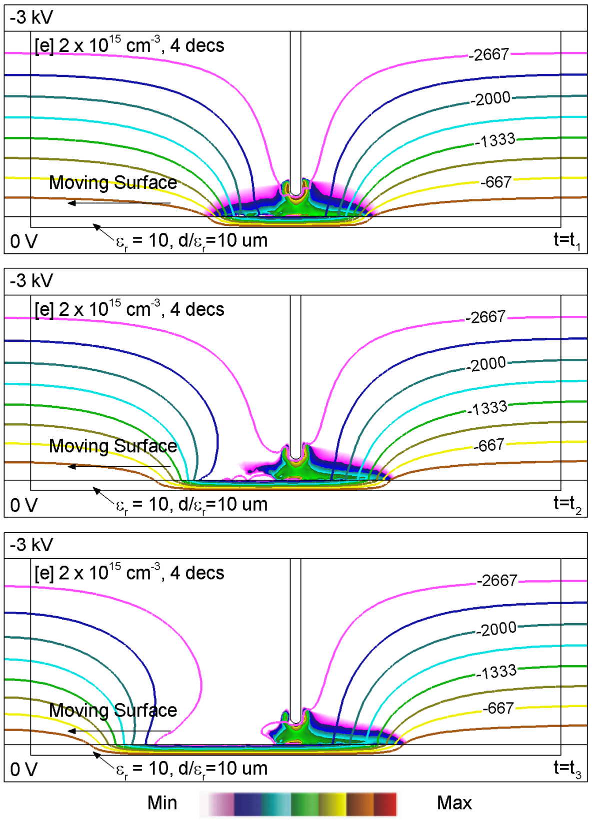

Figure 5. *Electron density in with the underlying surface moving from right to left. The images are from top-to-bottom for successive times. The electric potential is shown by the contour lines (labels are in volts).*

Moving Surface

When a corona discharge is used for charging and transfer steps in EP printing, the underlying dielectric is moving during charging process. For a stationary and previously uncharged PC, the surface charging is symmetric on either side of the wire. Surface charging reduces the local electric field and eventually terminates the corona discharge. In the case of a moving surface, as the underlying dielectric surface moves, surface charges are translated away from the corona wire on one side while uncharged dielectric translates towards the corona wire on the other side. The volume of the gas having a lower electric field also translates to the left as the charged surface moves. The incoming, uncharged surface enables a large electric field to sustain an electron avalanche.

The actual speed of the surface (either the PC or paper) is only tens of cm/s, which is difficult to address in the model while also simulating plasma processes having ns timescales. Instead, we translated the surface at a speed that is commensurate with the spreading of plasma. A time series of electron density in the corona discharge on this fast moving surface is shown in Fig. 5. The dielectric surface moves from right to left, carrying the deposited surface charges with it. The moving dielectric continually brings uncharged surface towards the corona wire. When the voltage drop between wire and uncharged surface rebounds, an electron avalanche occurs, and the corona discharge is then re-ignited. The corona discharge becomes asymmetric. The charged surface translating to the left suppresses the discharge while the incoming uncharged surface from the right enhances the discharge.

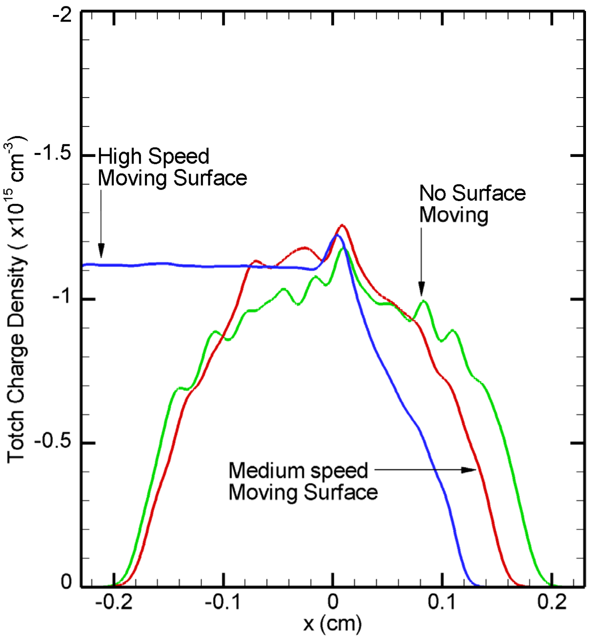

***Figure 6.** Total charge density profile (cm^{-3}) in a corona discharge with underlying surface either stationary or moving. The position of x=0 is directly underneath the corona tip.*

Total charge density profiles on the static and moving dielectric surface with high and medium speeds are shown in Fig. 6. On the stationary dielectric sheet, the surface ionization wave propagates outwards in a symmetric fashion and so charging is symmetric. The electron plumes encounter and continuously charge fresh uncharged surfaces. For medium speeds, there is some asymmetry to the charging. When the surface moves with a high speed the corona tip continually sees an uncharged surface entering from the right which is then continually being charged. As a result, there is not a great deal of propagation of the surface ionization wave to the right, while previously charged surface translates to the left. .

In an actual device, the surface moves in an almost quasi-static fashion which is much slower than the spreading of the plasma. The basic process is the same as discussed here, but in a less continuous manner, likely consisting of a series of discrete electron avalanches. For example, the corona discharge initially symmetrically charges the surface and the discharge terminates, while the surface charges slowly translate to the left. The electric field to the right slowly builds up as the uncharged surface approaches. When the electric field reaches a critical value, the electron avalanche is reinitiated, which then asymmetrically spreads on the surface until it too terminates. The process then repeats.

Concluding Remarks

Corona electric discharges sustained in atmospheric pressure gases are important in many EP printing technologies to charge the PC surfaces. We computationally investigated the properties of an idealized corona discharge and surface charging when the charged surface is stationary and moving. We found that at the initial stage of discharge, ionization by sheath accelerated secondary electrons is comparable to electron impact ionization from bulk plasma directly underneath the corona tip. Electrons charge the underlying dielectric negatively, and electric potential lines are trapped in the dielectric. On a stationary dielectric, a surface ionization wave spreads along the PC outward from the wire and symmetrically charges the dielectric surface. The discharge is eventually terminated by the reduced voltage drop between the corona wire and the avalanche front on the surface. We also found that higher electron and surface charge densities are produced on dielectrics of higher capacitance due to there being a larger potential drop in the gap and longer charging times. When the underlying surface is moving, surface charges and the potential they produce are translated away from the corona wire. Voltage between the corona wire and the incoming uncharged surface rebounds, and an electron avalanche is reinitiated. The corona discharge process then repeats. For these conditions, the discharge only occurs on the side of the corona wire with the incoming uncharged surface, and surface charging patterns become asymmetric.

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Author Biographies

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Henryk Birecki is a Senior Scientist at Hewlett Packard Laboratories. He received PhD in physics from the Massachusetts Institute of Technology in 1976 and joined HP Labs in 1978. While at HP he has worked on displays, optical computing, optical recording and other mass storage technologies. He managed projects on optical recording materials and devices and organized international conferences on the subject. Since 2006 he has been working on printing technologies.

Omer Gila is managing the “Printing Processes for Digital Commercial Print” department in HP Labs Palo Alto California. Prior to HP Labs, Omer held the positions of COO of Oniyah PSP in Israel and the color control manager in Indigo Rehovot. He holds a B.Sc. (1989) in Physics and Mathematics from the Hebrew University (Jerusalem, Israel) and M.Sc. (1992) in Applied Physics and Electro-optics from the Weizmann Institute of Science (Rehovot, Israel) with honors in both.