Modeling and Numerical Analysis for Motional Effects of Dielectric Barrier on Electric Discharge and Surface Charge Accumulation

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***Abstract*—Dielectric barrier discharge is modeled with discharge equations, which consist of hydrodynamic drift-diffusion equations for space charge density variation and Poisson's equation for electric field distribution. These equations are numerically analyzed using finite element scheme. Analysis object consists of two cylinder electrodes, which is covered with dielectric material. Space charges generated during discharge are accumulated on dielectric barrier, and it affects electric field distribution. In this paper, dielectric barrier discharge is analyzed taking into account the rotation of electrodes with surface charge. The surface potential of electrode coated with dielectric material is measured and it is compared with the one calculated from the discharge analysis. The analysis results show good agreement with the surface potential of experiment.**

***Index Terms*—Dielectric barrier discharge, space charge distribution, electromagnetic coupling, finite element scheme**

I. Introduction

Discharges in the presence of dielectric barrier are called dielectric barrier discharges (DBDs), that have been being applied in many devices and processes such as laser printer, thin film deposition, plasma display panels, ozone production, sterilization and gas treatment, surface treatment, and aerodynamic boundary layer control [1]. In printers and copiers, DBD is used for charging roller system that consists of a charge roller and an organic photoconductor. To analyze the charging roller system, Paschen limit to calculate surface potential of organic photoconductor has been employed [2]. However, the Paschen limit does not well explain discharge process where ionization, recombination and attachment phenomenon occur.

In this paper, the dielectric barrier discharge between two electrodes coated with dielectric material is analyzed using three discharge equations and one field equation. A Gaussian distribution of neutral plasma for charge injection condition is employed at dielectric barrier surface when electric field intensity reaches a breakdown condition. These injected charges experience electric force, and move towards a cathode or an anode, respectively. The space charges are generated because neutral molecules are ionized due to collision with electrons. The velocity of space charge is calculated using the electric field from Poisson's equation, and this is coupled with the hydrodynamic equation for charge motion and density.

In the analysis model, the charges accumulated on the dielectric barrier move along with the cylinder electrode at a given velocity. The surface charge distribution obtained at some instant is used as another initial condition for the discharge analysis at the next position of the moving electrode. The calculated surface potential of dielectric barrier is compared with the measured one to show that the proposed analysis method is feasible and useful for the discharge analysis with the motional effect.

II. Modeling of Dielectric Barrier Discharge

A. Hydrodynamic Drift-Diffusion Models

The motion of electrons, and positive and negative ions can be calculated using hydrodynamic drift-diffusion equations derived from the continuity equation. Three mathematical expressions for reactions between the three changes of the electron (ρ_e), positive (ρ_p), and negative (ρ_n) ions with respect to time are provided as follows [3-4]:

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot \left(\rho_i \mathbf{v}_i + D_i \nabla \rho_i\right) = \alpha \rho_e v_e \pm \eta \rho_e v_e - \beta_{ij} \rho_i \rho_j - \beta_{ik} \rho_i \rho_k \quad (1)$$

where t, $\mathbf{v}_i$ and D_i denotes the time, the drift velocity and diffusion coefficient of space charge, respectively, and α, η and β are the ionization, attachment and recombination coefficients, respectively. The attachment coefficient is of negative sign for the calculation of electron density ($i = e$); $j = p$ and $k = 0$. The positive ion density ($i = p$) is obtained using $\eta = 0$, $j = e$ and $k = n$. In the case of the negative ion density ($i = n$), the ionization and attachment coefficient are zero and of positive sign, respectively; $j = p$ and $k = 0$.

The motion of charged species is affected by an electric field because its velocity is expressed as follows:

$$\mathbf{v}_i = \mu_i \mathbf{E} \quad \textit{where } i = e, p, n \quad (2)$$

where μ_i is the mobility of each space charge, and $\mathbf{E}$ is the electric field. Therefore, each hydrodynamic equation is coupled with Poisson's equation.

B. Electrostatic Model with Dielectric Barrier

The continuity equations are solved along with Poisson's equation, resulting in an expression for electric field distributions each time, as by the following expression:

$$\nabla \cdot \left(-\varepsilon \nabla V\right) = \rho_p - \rho_e - \rho_n \quad (3)$$

where ε, and V are the dielectric permittivity, and the electric scalar potential, respectively. In the presence of a dielectric barrier, space charges can accumulate on its surface, and this affects electric field distribution. Therefore, we consider the change of surface charge on a dielectric barrier for calculating electric field distribution.

The surface charge density can be calculated by integrating the current density of each charged species as follows:

$$\sigma_s(t) = \int_0^t (\mathbf{J}_e + \mathbf{J}_n + \mathbf{J}_p) \cdot \mathbf{n} dt \quad (4)$$

where σ_s is the surface charge density, and charge fluxes through the surface as expressed in (5).

$$\mathbf{J}_i = \rho_i \mathbf{v}_i \quad (5)$$

where i is e, n and p. The surface charge affects electric field distribution in a dielectric barrier discharge system. That is, Poisson's equation for electric field is revised as follows:

$$\nabla \cdot (-\varepsilon \nabla V) = \rho_p - \rho_e - \rho_n + \sigma_s \quad (6)$$

III. Numerical Analysis of Discharge Between Charging Roller and Photoconductor

A. Analysis Model Description

The outer and the inner diameter of upper electrode are 16mm and 8mm, respectively. The outer diameter of lower electrode, which has a dielectric material with 25µm thickness, is 24mm. In this system, the discharge occurs within small region; about 1.5mm width and 200µm height. The whole model is shown in Fig. 1, left side, and the analysis model is in right side. The negative voltage, -1.2kV, is applied in the upper electrode, and the lower electrode is ground.

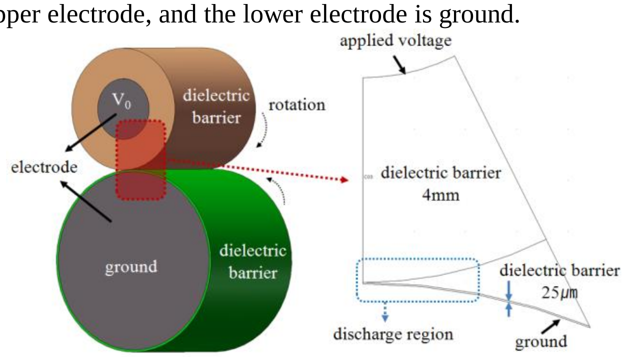
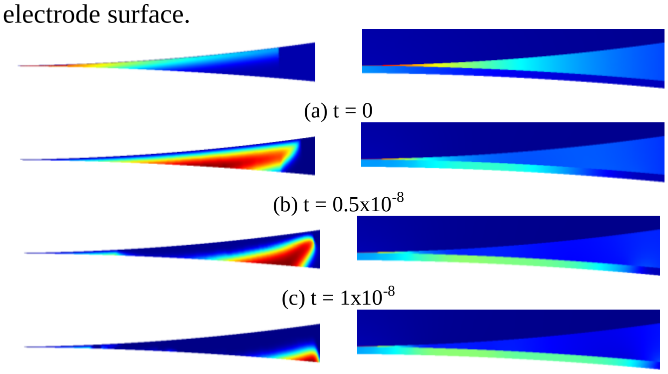


Fig. 1. 2D analysis model of charging roller system

B. Space Charge Propagation and Electric Field

Neutral molecules can be ionized more than electric field intensity, $3\times10^6 \mathrm{V \cdot m^{-1}}$. A Gaussian distribution of neutral plasma for charge injection condition is employed at upper electrode surface.



(a) t = 0

(b) t = 0.5×10^{-8}

(c) t = 1×10^{-8}

(d) t = 1.5×10^{-8}

Fig. 2. Electron distribution in space (left) and electric field distribution (right) as time

While the electrons move towards the lower electrode, its density increases exponentially due to ionization of neutral molecules. Electric field distribution varies as charge accumulation on the lower electrode.

C. Surface Charge Accumulation and Potential

The surface charge distribution on the lower electrode as time is shown in Fig. 3. Even though the field intensity is strong near the contact between two electrodes, the electron density generated during discharge is smaller than the middle of the lower electrode because the mean free path of electron is related to ionization.

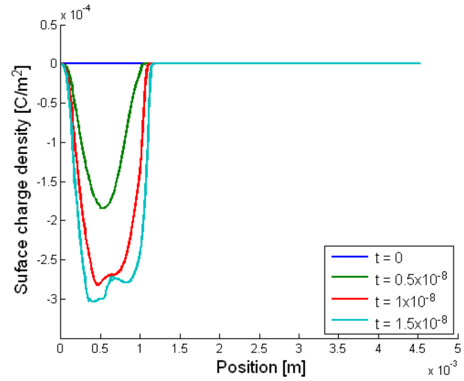


Fig. 3. Surface charge density on the lower electrode

The average of surface charge density is used for the boundary condition of next step analysis when the surface charge on the lower electrode is saturated. Figure 4 shows the surface charge density on the lower electrode at inlet and outlet region.

In the full paper, the numerical analysis method for surface charge movement due to rotation will be discussed in detail. The analysis results will be compared with the existing results.

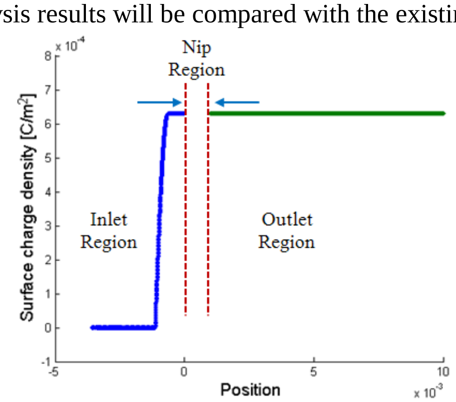


Fig. 4. Surface potential on the lower electrode

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