# Fully Coupled Finite Element Analysis for Surface Discharge on Solid Insulation in Dielectric Liquid with Experimental Validation

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**In this paper, we examined the behavior of surface discharge initiation and propagation on the surface of insulating solid immersed in dielectric liquid. To build a generalized numerical technique for the surface discharge phenomena with the electrohydrodynamics (EHD) approach, we employed the Navier-Stoke's equation and introduced the temporal surface charge equation for charge accumulation on a dielectric liquid-solid interface as well as the ionization, dissociation, and recombination effects. To verify the numerical setup, the numerical result was compared to that of experiment obtained from the literature.**

***Index Terms*—Dielectric liquids, Electrohydrodynamics, Finite element analysis, Insulators, Surface discharges.**

## I. Introduction

IT has been pointed out that the electrical insulation is the most important technique for electrical equipment including transformers, circuit breakers, vacuum interrupter, and cables. In power electrical systems such as power transformer, most failures of insulation systems are related to the breakdown of solid insulators [1]. The electrical breakdown prediction is to become a critical issue which is the electric discharge process in power applications. The fully coupled analysis technique for generalized electrohydrodynamics has been developed recently in the liquid discharge area [2]-[4]. This technique concentrates on the electric field dependent molecular ionization and ionic dissociation without surface discharge, tracking. The discharge mechanism for tracking, however, is important to understand the breakdown phenomena with dielectric media but the detailed mechanism has not been fully determined yet.

To analyze this breakdown process quantitatively, we coupled the governing equations based on the charge continuity equations for positive ion, negative ion and electron, the energy balance equation, and the Poisson's equation. By using these fully coupled equations, we conducted to analyze tracking at the dielectric liquid-solid interface. The free charge was assumed zero in the solid region which was modeled as a perfect insulator. Additionally, to simulate the tracking more accurately, charge dynamics should be calculated considering the surface charge accumulation. Finally, the fully coupled Finite Element model was successfully applied to the prediction of tracking.

## II. Electro-Hydrodynamic Governing Equations

The generalized hydrodynamic drift-diffusion equations combined with the Poisson's equation have been widely employed for analyzing discharge analysis in dielectric liquids. In addition to these equations, here, we added an additional velocity term for fluidic flow stressed by the electric field resulting in the Nernst-Plank equation for each continuity equation. The Navier-Stoke's equation was employed for momentum energy and the energy balanced equation, for temperature. Those governing equations were fully coupled with each other as follows [2]-[4]:

$$-\nabla\cdot(\varepsilon\nabla V)=\rho_+ + \rho_- + \rho_e \tag{1}$$

$$\frac{\partial\rho_+}{\partial t}+\nabla\cdot\mathbf{J}_+ = G_I(|\mathbf{E}|)+G_D(|\mathbf{E}|,T)+\frac{\rho_+\rho_-R_\pm}{e}+\frac{\rho_+\rho_-R_{+e}}{e}-\mathbf{v}\nabla\rho_+ \tag{2}$$

$$\frac{\partial\rho_-}{\partial t}+\nabla\cdot\mathbf{J}_- = -G_D(|\mathbf{E}|,T)-\frac{\rho_+\rho_-R_\pm}{e}+\frac{\rho_e}{\tau_a}-\mathbf{v}\nabla\rho_- \tag{3}$$

$$\frac{\partial\rho_e}{\partial t}+\nabla\cdot\mathbf{J}_e = -G_I(|\mathbf{E}|)-\frac{\rho_+\rho_-R_{+e}}{e}-\frac{\rho_e}{\tau_a}-\mathbf{v}\nabla\rho_e \tag{4}$$

$$\frac{\partial T}{\partial t}+\mathbf{v}\cdot\nabla T=\frac{1}{\rho_l c_v}(k_T\nabla^2 T+\mathbf{E}\cdot\mathbf{J}) \tag{5}$$

$$\rho_l\frac{\partial\mathbf{v}}{\partial t}-\nabla\cdot[\eta(\nabla\mathbf{v}+(\nabla\mathbf{v})^T)]+\rho_l(\mathbf{v}\cdot\nabla)\mathbf{v}+\nabla p=\mathbf{F} \tag{6}$$

$$\nabla\cdot\mathbf{v}=0 \tag{7}$$

where the subscript +, −, and $e$ denote the positive, negative ions, and electron, respectively, $G_I(|\mathbf{E}|)$ molecular ionization, and $G_D(|\mathbf{E}|,T)$ ionic dissociation source term, $R$ recombination rate, $\tau_a$ electron attachment time constant, $\mathbf{v}$ fluidic velocity, $\mathbf{E}\cdot\mathbf{J}$ represents the electrical power dissipation term in the fluidic medium. $\mathbf{F}$ is the body force density including the Coulomb force for charges, the Kelvin force density for the electric field gradient, and the Boussinesq buoyant force for temperature gradient.

The governing equation in solid insulation was the Gauss's law with zero space charge as follows:

$$-\nabla\cdot(\varepsilon\nabla V)=0 \tag{8}$$

$$\nabla\cdot\mathbf{J}_{SD}=0 \tag{9}$$

$$\frac{\partial T}{\partial t}=\frac{1}{\rho_{SD}c_{SD}}(k_{SD}\nabla^2 T) \tag{10}$$

where the current density $\mathbf{J}_{SD}$ is zero because the solid insulator has zero conductivity. $\rho_{SD}$ is the mass density, $c_{SD}$ is the specific heat capacity, and $k_{SD}$ is the thermal conductivity in the solid insulator region.

## III. Calculation of Surface Charge Accumulation at Dielectric Liquid-Solid Interface

The surface charge density, $\sigma_s$, at the dielectric liquid-solid interface can be calculated as

$$\frac{\partial \sigma_s}{\partial t} = \mathbf{n} \cdot (\mathbf{J}_+ + \mathbf{J}_- + \mathbf{J}_e) \tag{11}$$

where $\mathbf{J_i} = \rho_i \mu_i \mathbf{E}$ and $\mathbf{n}$ is the outward normal unit vector from solid to liquid. To determine the surface charge density in Poisson's equation, the surface charge density can be calculated using Gauss's law as

$$\mathbf{n} \cdot (\mathbf{D_{solid}} - \mathbf{D_{liquid}}) = \sigma_s \,. \tag{12}$$

## IV. Results and Discussion

To analyze the surface discharge, tracking, numerical and experimental setup was constructed with the tip-plate electrodes and the dielectric liquid-solid interface as shown in Fig. 1. Fig. 2 shows that the propagations of electric field and normalized dielectric liquid flow due to the surface charge density on the interface of dielectric solid. The order of the initial electric field intensity around the head of the tip was approximately $10^8$ V/m, which is sufficient for the initiation of streamer and for the traveling along with the dielectric liquid-solid interface [3]-[4]. Fig. 3 shows the distributions of temporal dynamics of electric field and surface charge density obtained from the fully coupled multiphysics analysis. With this numerical simulation, the propagating speed of surface discharge was approximately 11.1 km/s. As can be seen from Fig. 3 and Table 1, our numerical result has good agreement with that of experiments from the previous literatures [5]-[6].

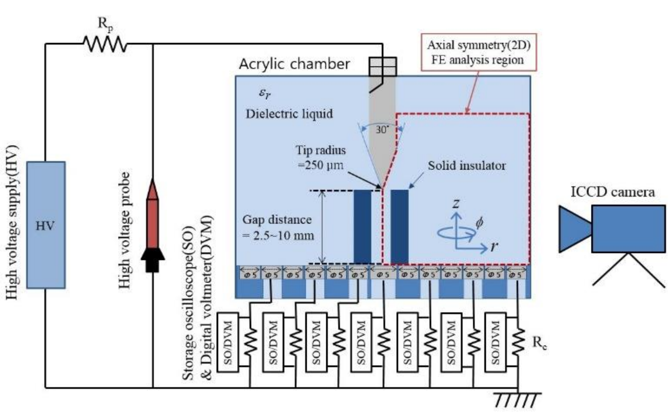
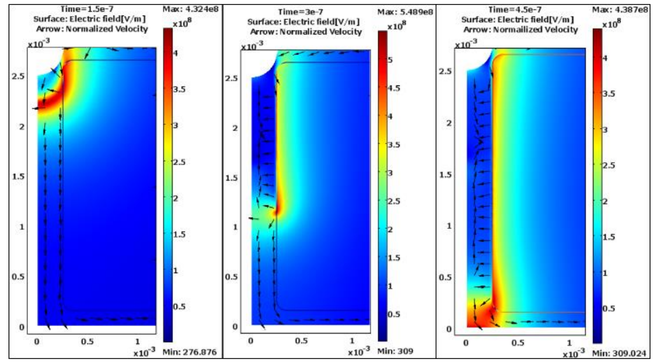
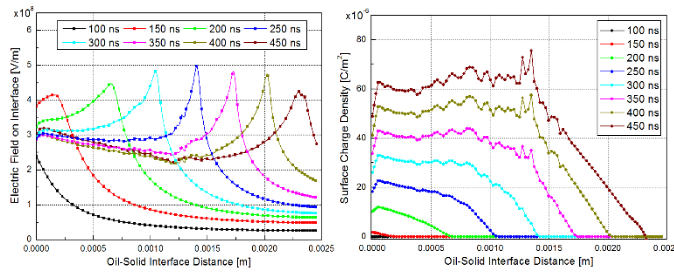



Fig. 1. Schematic representation for the experimental set-up and numerical validation with tip-plates model with dielectric solid (liquid-solid interface)



(a) t = 15 μs (b) t = 30 μs (c) t = 45 μs

Fig. 2. Distributions of normalized vector fluidic flow as arrows and temporal electric field as surface plot with each time step.




(a) Electric field (b) Surface charge density

Fig. 3. Temporal dynamics of the electric field and surface charge density with the step voltage of 20 kV and 100 ns rising time.

TABLE I
Comparisons Of Breakdown Velocity With Tube Interface

| Method | Breakdown Velocity [km/s] |
|---|---|
| Experiment [5]-[6] | 12.0 |
| Simulation | 11.1 |

## V. Conclusion

The result of this study suggests the validation of surface discharge, tracking, in dielectric liquid with solid insulator numerically and experimentally. In an extended paper, more interesting results and physical explanations will be studied in detail with our experimental results.

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