Numerical Analysis for Surface Discharge on Solid Insulation in the Dielectric Liquid with Experimental Validation

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Introduction: Surface discharge initiation and propagation on the surface of an insulating solid immersed in a dielectric liquid were examined numerically and experimentally. To establish a generalized numerical technique for evaluating surface discharge phenomena using the electrohydrodynamics (EHD) approach, we employed the governing equations of EHD, including the Navier–Stokes equations. To these coupled governing equations, we added a temporal surface charge equation for charge accumulation on a dielectric liquid–solid interface, as well as terms for ionization, dissociation, and recombination effects. To validate our numerical technique, we compared numerical solutions for breakdown voltage and current with the results of experimental tests of a needle-bar system with a dielectric liquid–solid interface. The calculated propagation speeds of surface discharge were compared with experimental values reported in the literature and were found to be in good agreement.

Generalized EHD model:

Dielectric Liquid (Transformer Oil ε_r=2.2) | **Perfect Solid Insulator (Pressboard ε_r=4.3)**

■ **Charge Transport Equations**

Dielectric liquid:

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

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

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

Solid insulator:

$$\nabla \cdot \mathbf{J}_S = 0 \quad \text{with } \mathbf{J}_S = \sigma_S \mathbf{E}_S$$

■ **Poisson's Equation**

$$\nabla \cdot (-\varepsilon \nabla V) = \rho_+ + \rho_- + \rho_e \qquad \nabla \cdot (-\varepsilon \nabla V) = 0$$

Fully Coupled with FEM !

■ **Energy Balance Equation**

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

■ **Navier-Stokes Equation**

$$\rho_l \frac{\partial \mathbf{v}}{\partial t} - \nabla \cdot [\eta(\nabla \mathbf{v} + (\nabla \mathbf{v})^T)] + \rho_l (\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla p = \mathbf{F}_{tot} \quad \text{with} \quad \nabla \cdot \mathbf{v} = 0$$

➢ **Surface Charge Density at Oil-Solid Interface**

$$\frac{\partial \sigma_{surface}}{\partial t} = \mathbf{n} \cdot (\mathbf{J}_{C,oil} - \mathbf{J}_S)$$

$$\mathbf{n} \cdot (\mathbf{D}_{oil} - \mathbf{D}_S) = \sigma_{surface}$$

➢ **Electric and Buoyant Body Force Density**

$$\mathbf{F}_{tot} = \mathbf{F}_{KH} + \mathbf{F}_{buoy} = \underbrace{\rho_f \mathbf{E}}_{\text{Coulomb's Force for Free Ion Charge}} + \underbrace{\mathbf{P} \cdot \nabla \mathbf{E}}_{\text{Kelvin Polarization Force}} + \underbrace{\rho_l \beta (T - T_{ref})\mathbf{g}}_{\text{Boussinesq Buoyancy Force}}$$

Results: Some functions and user defined equations were added via COMSOL Multiphysics and the detailed numerical setup was implemented in that program.

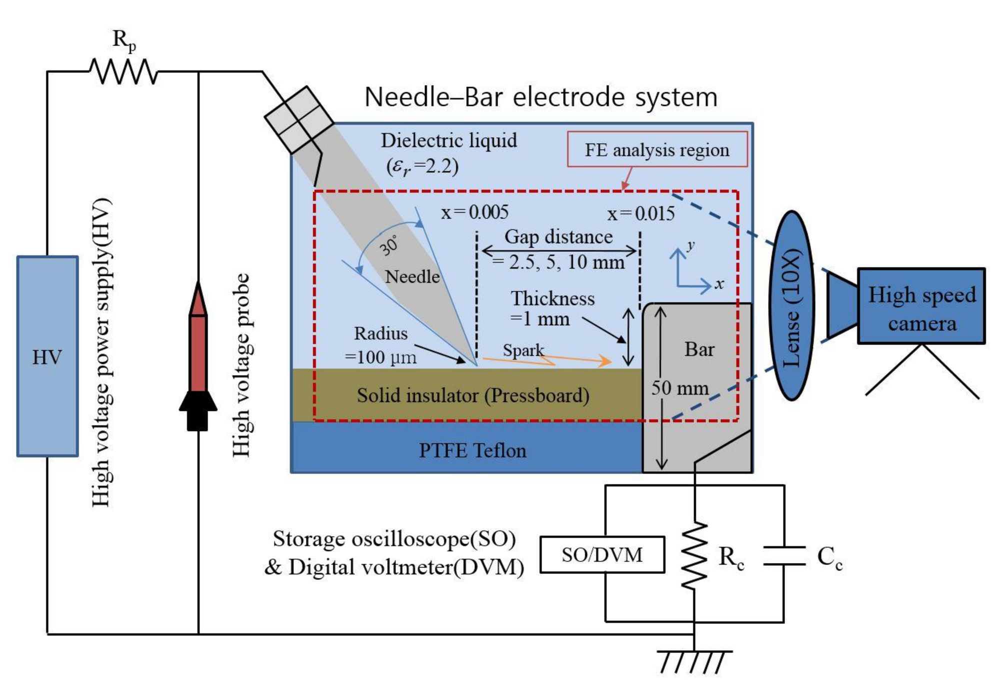

Fig. 1. needle-bar electrode system

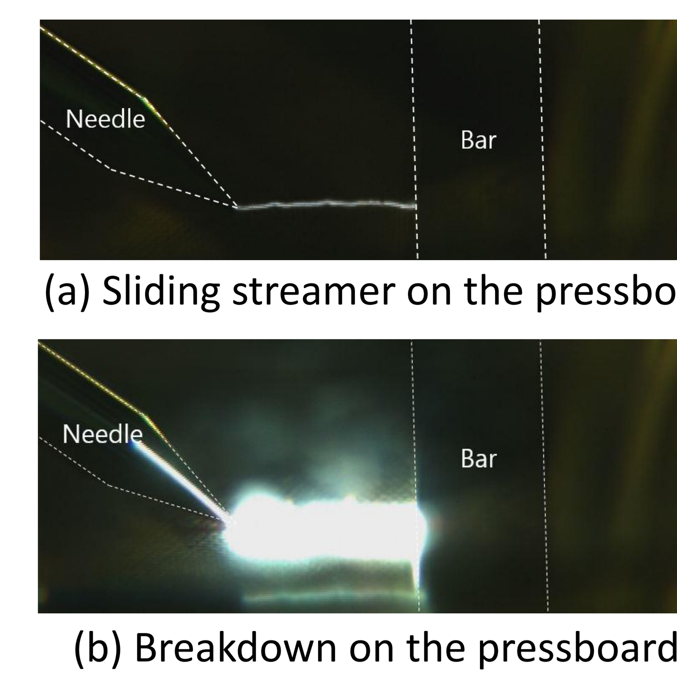

Fig. 2. Snapshot of surface discharge in dielectric liquid

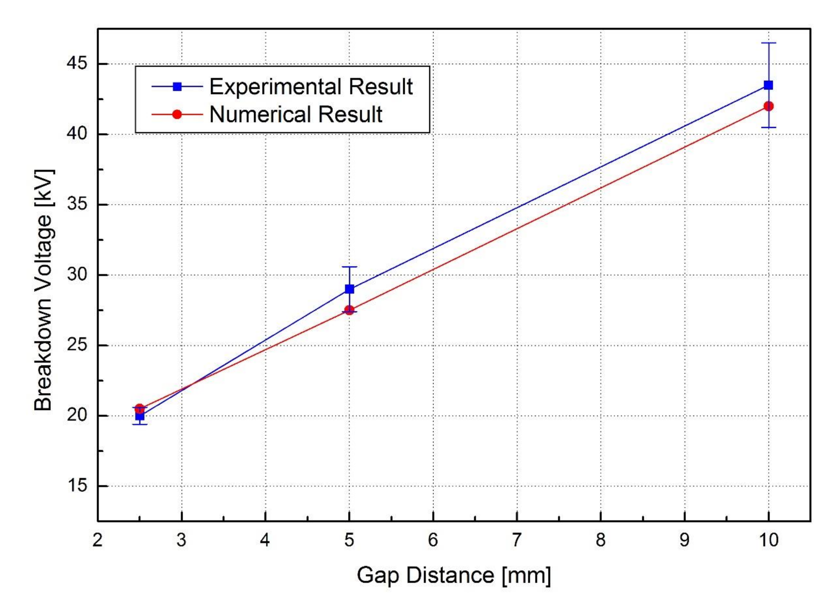

Fig. 3. breakdown voltage versus gap distance

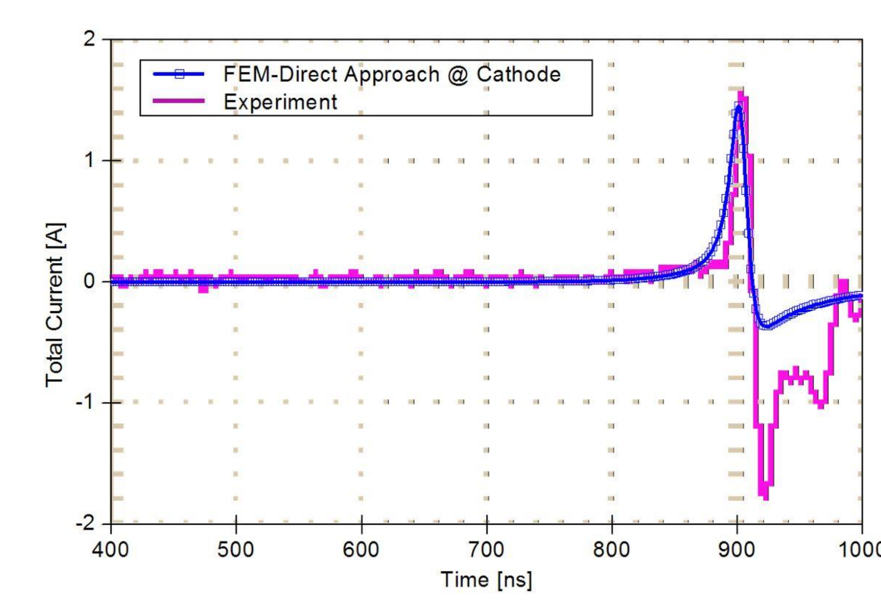

Fig.4. Comparison of surface discharge current

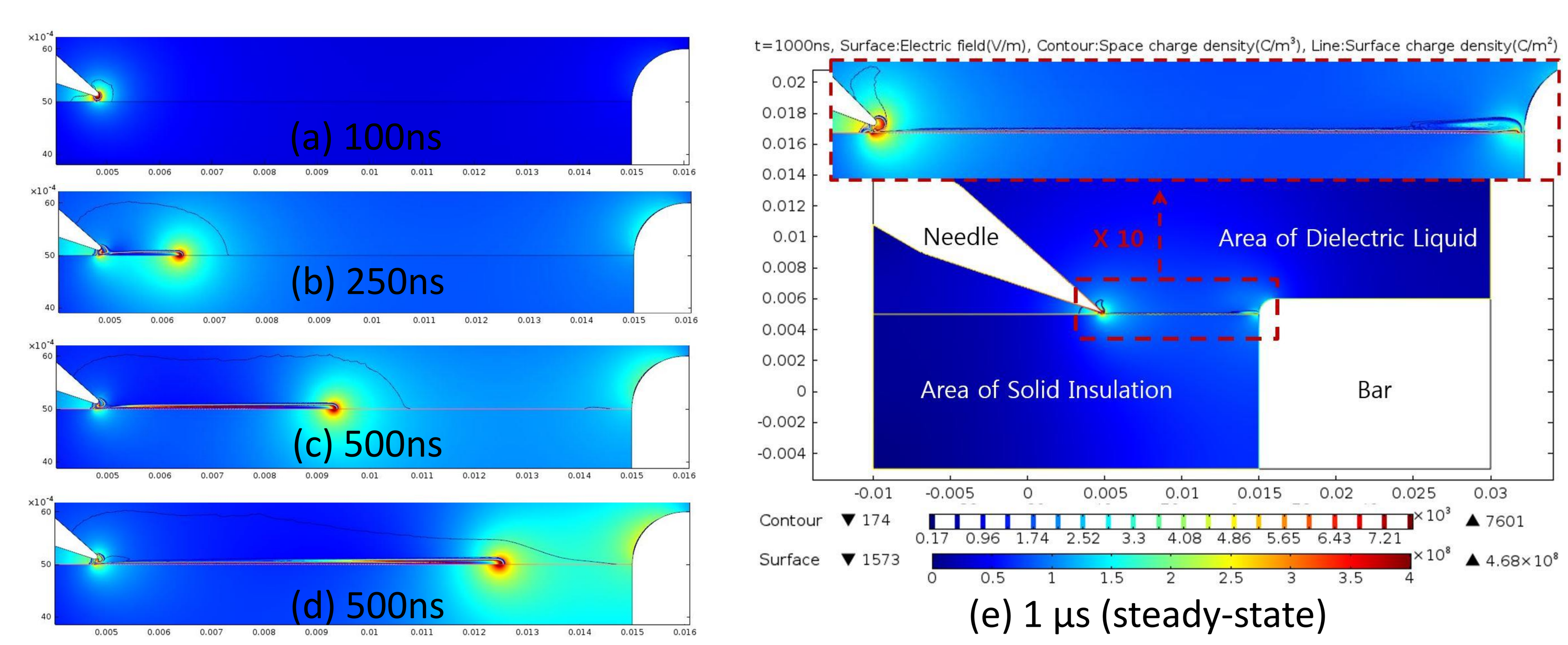

Fig. 5. Distributions of temporal electric field intensity as surface plot and space charge density as contour plot for various time steps

Table 1. Comparison of average breakdown velocity with solid insulator

Method	Breakdown Velocity [km/s]
Experiment [11]-[12]	12.0
Simulation	11.1

Conclusions: The results of this study confirm the validity of the numerical and experimental approaches used to modeling surface discharge and tracking in dielectric liquid with a solid insulator. A fully coupled finite element model was developed and validated using an experimental setup. A needle-bar electrode system was tested with a dielectric liquid–solid interface. The numerical results were found to be in good agreement with the experimental results. The simulated speed of surface charge propagation was found to be in good agreement with experimental results reported in the literature.

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