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 $\varepsilon_r=2.2$)
- **Perfect Solid Insulator** (Pressboard $\varepsilon_r=4.3$)

<table>
<thead>
<tr>
<th>Charge Transport Equations</th>
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<tr>
<td>( \frac{\partial J_y}{\partial t} + \nabla \cdot (\sigma_v E) = 0 )</td>
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Poisson's Equation

\[ V \cdot (-\nabla V) = \rho_s + \rho_e + \rho_v \quad V(-\nabla V) = 0 \rightarrow \text{Fully Coupled with FEM!} \]

Energy Balance Equation

\[ \frac{\partial T}{\partial t} + \nabla \cdot ((k_v\nabla T + E \cdot J) = \frac{\partial}{\partial t} (k_v \nabla T) \]

Navier-Stokes Equation

\[ \frac{\partial}{\partial t} \nabla (\rho (v \cdot v)) + \frac{\partial}{\partial x} (\rho v_1 v_2 + \rho v_1 v_2) = \nabla \cdot (\nabla ) \]

Surface Charge Density at Oil-Solid Interface

\[ \frac{\partial \sigma_{\text{surf}}}{\partial t} = \nabla \cdot (J_{\text{ion}} - J_s) \]

Electric and Buoyant Body Force Density

\[ F_{\text{tot}} = F_{\text{KH}} + F_{\text{buoy}} = \frac{1}{\varepsilon} \nabla E \cdot \varepsilon_0 \frac{\rho_b}{\varepsilon_0} \]

Kelvin Polarization Force

Boussinesq Buoyancy Force

Coulomb's Force for Free Ion Charge

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](image1)

![Fig. 2. Snapshot of surface discharge in dielectric liquid](image2)

![Fig. 3. breakdown voltage versus gap distance](image3)

![Fig. 4. Comparison of surface discharge current](image4)

![Fig. 5. Distributions of temporal electric field intensity as surface plot and space charge density as contour plot for various time steps](image5)

| 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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