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Hybrid Resistive-Capacitive and Ion Drift Model for Solid Gas Dielectrics

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Outline

- Introduction to Gas Insulated Switchgear (GIS)
- DC Dielectrics and the Ion Drift Model
- COMSOL Implementation of Hybrid Model
- Results
- Conclusions and Outlook

Gas Insulated Switchgear (GIS)

- Gas insulated switchgear is a compact metal encapsulated switchgear consisting of high-voltage components such as circuit-breakers and disconnectors.
- The main electrical insulation in GIS (separating high voltage and ground) consists of SF6 gas and epoxy spacers.
- GIS is used particularly when there are space constraints, since the systems are much more compact compared to air insulated systems.

DC Dielectrics

- To understand the properties of a dielectric system, the electric field distribution needs to be simulated.
- High electric field can overstress the dielectric materials causing failure of the electrical insulation system.
- At voltage switch on (zero net charge) the field can be calculated using the Laplace equation.
- Under DC stress the system will evolve due to transport of charge which changes the electric field.
- One of the main challenges for DC dielectric is to find a good model for charge transport.

$$-\nabla \cdot (\varepsilon \nabla \varphi) = \rho$$

$$\vec{E} = \nabla \varphi$$

$$\frac{d\rho}{dt} = -\nabla \cdot \vec{J}(\vec{E}, \dots)$$

Charge transport solids
Ohm's Law

- For solid dielectrics Ohm's law usually works sufficiently well over a range of electric field strengths.
- The coupling the equation with Poisson's equation gives a model for solid dielectric usually referred to as a Resistive-Capacitive (RC) model.

$$\vec{J} = \sigma \vec{E}$$

Charge Transport Gas
Ion Drift Model

- In a gas Ohm's law works less well, since the charge transport is often limited by the amount of available ions.
- A better model is the ion drift model, which takes the charges explicitly into account. The model is formulated using drift-diffusion equations.
- Below critical field levels the source term is dominated by background ion production from processes such as cosmic rays.

$$\frac{dp}{dt} + \nabla \cdot \left(\mu\vec{E}p - D\nabla p\right) = R$$

$$\frac{dn}{dt} - \nabla \cdot \left(\mu\vec{E}n + D\nabla n\right) = R$$

$$\rho = q \cdot (p - n)$$

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COMSOL Implementation of the Hybrid Model
Overview of interfaces and boundary conditions

Model	Resistive-capacitive	Ion drift model
COMSOL interface	Electric currents	2 x Transport of diluted species
Solid material	Constant conductivity (Ohm's law)	-
Gas	Very low (near zero) conductivity	Ion drift equations with constant source term
External boundaries	Electric potential	Open boundary
Gas solid boundary	Boundary current source based on the flux from the ion drift equations.	Open boundary

Quasi Stationary Approximation for the Ion Flow

- The time of flight for an ion is typically a fraction of a second, much shorter than the time scale of the system.
- The flow pattern of ions is close to equilibrium at any given time. The flow can therefore be modeled as quasi stationary by removing the time derivative.
- The approximation greatly speeds up the simulation and improves the numerical stability.
- The main error introduced is directly after a voltage change when the flow is in non-equilibrium. This is a very small contribution to the total charge.

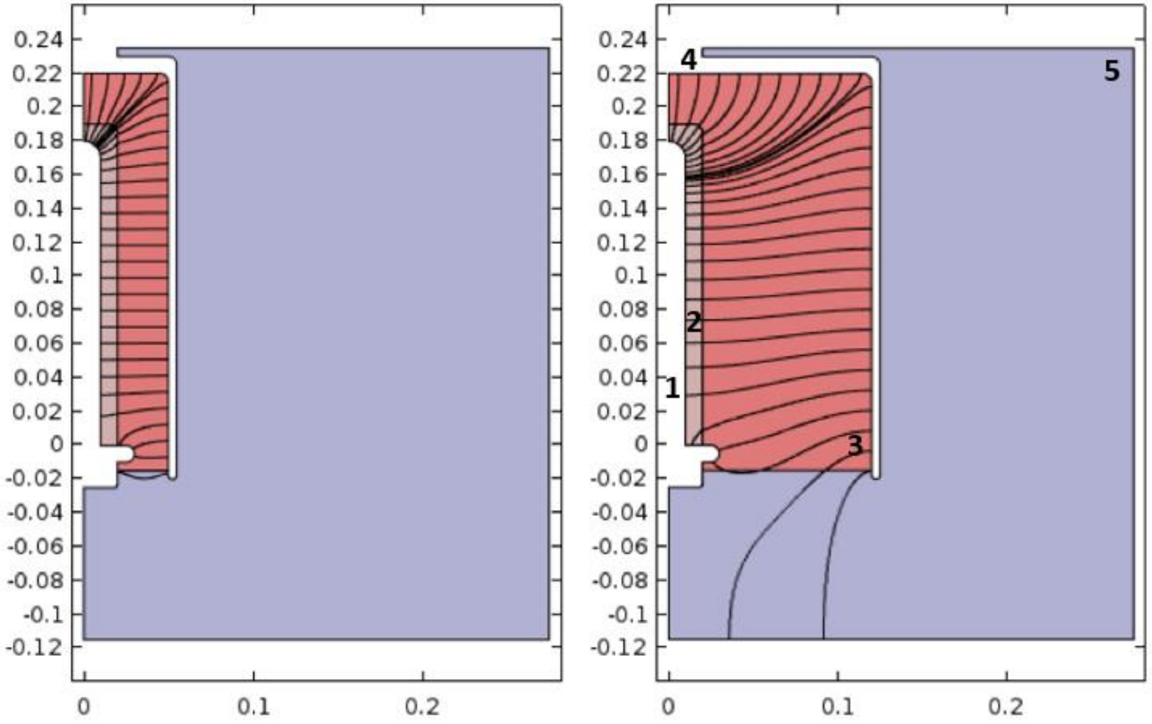
$$\frac{dp}{dt} + \nabla \cdot \left(\mu \vec{E} p - D \nabla p\right) = R$$

$$\xrightarrow{Approx.}$$

$$\nabla \cdot \left(\mu \vec{E} p - D \nabla p\right) = R$$

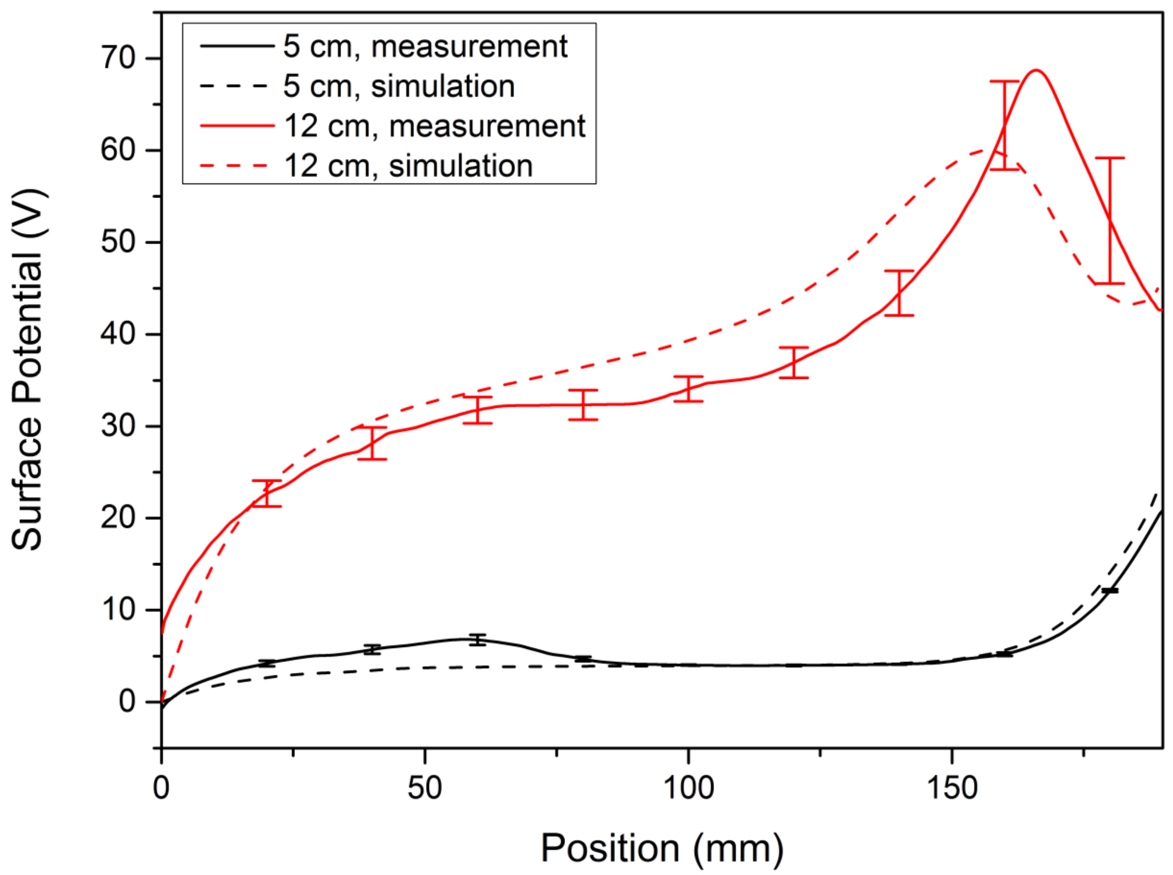
Simulated Geometries

- Two geometries were simulated, both measured at ETH Zürich.
- The test geometries are designed to measure the effect of different gas volumes.
- A grounded electrode (1) enclosed in epoxy (2) is surrounded by a high voltage electrode (4) placed in SF6 gas (3) and (5). Both geometries are axisymmetric.
- 1kV is applied to the electrode for 12 hours and the surface potential measured along the epoxy surface.



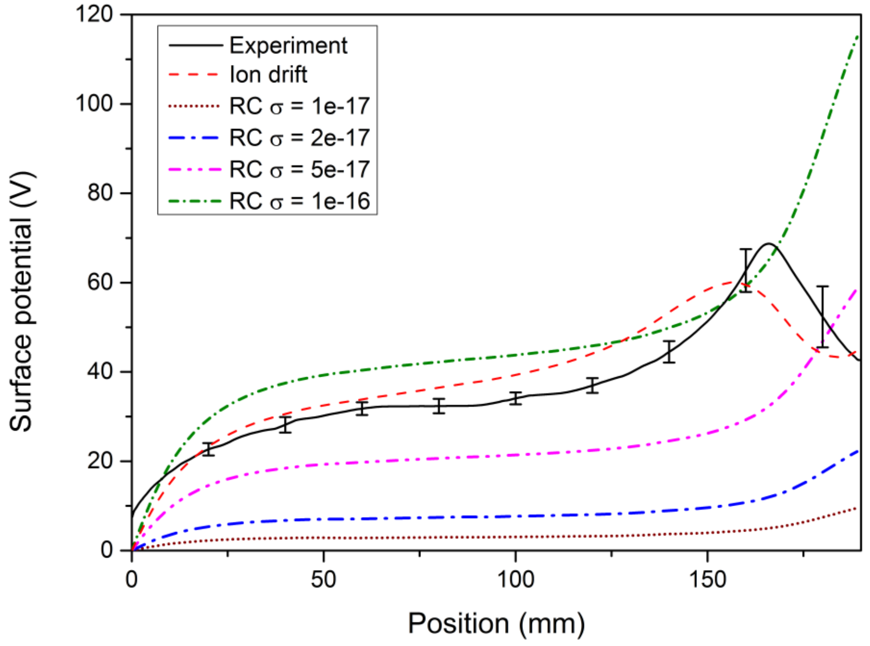
Results with the Hybrid Model

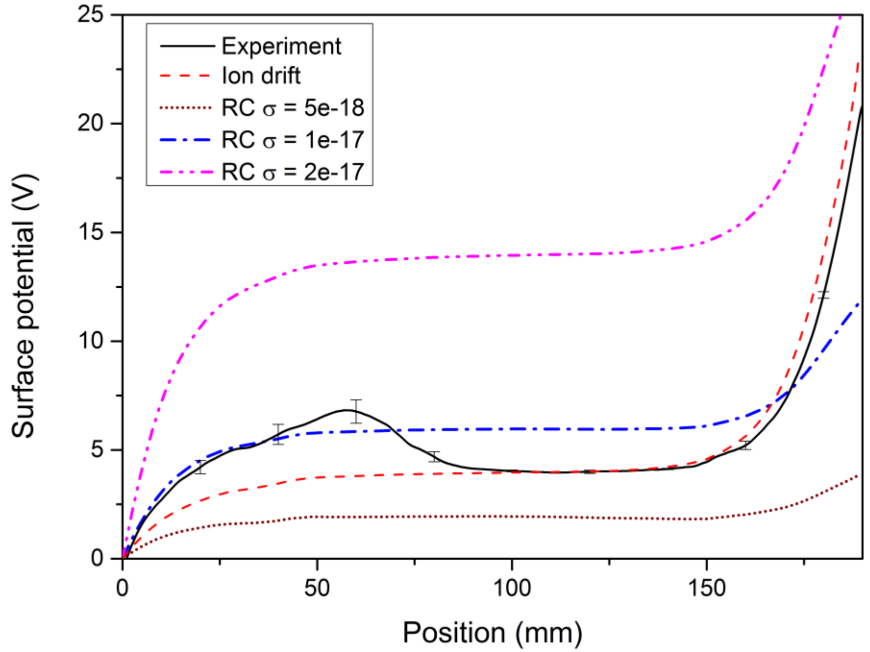
- The results from the simulations are compared to experimental data from ETH Zürich.
- The background ion production and epoxy resistivity are fit to data.
- All the main features are captured and the match to data is very satisfactory.
- The simulation time is around 1 min in COMSOL.



Data taken from M. Schueller and C.M. Franck, Influence of the Gas Volume Size on Spacer Charging in SF6 under DC Stress, *ISH* 2013.

Comparison with an RC model

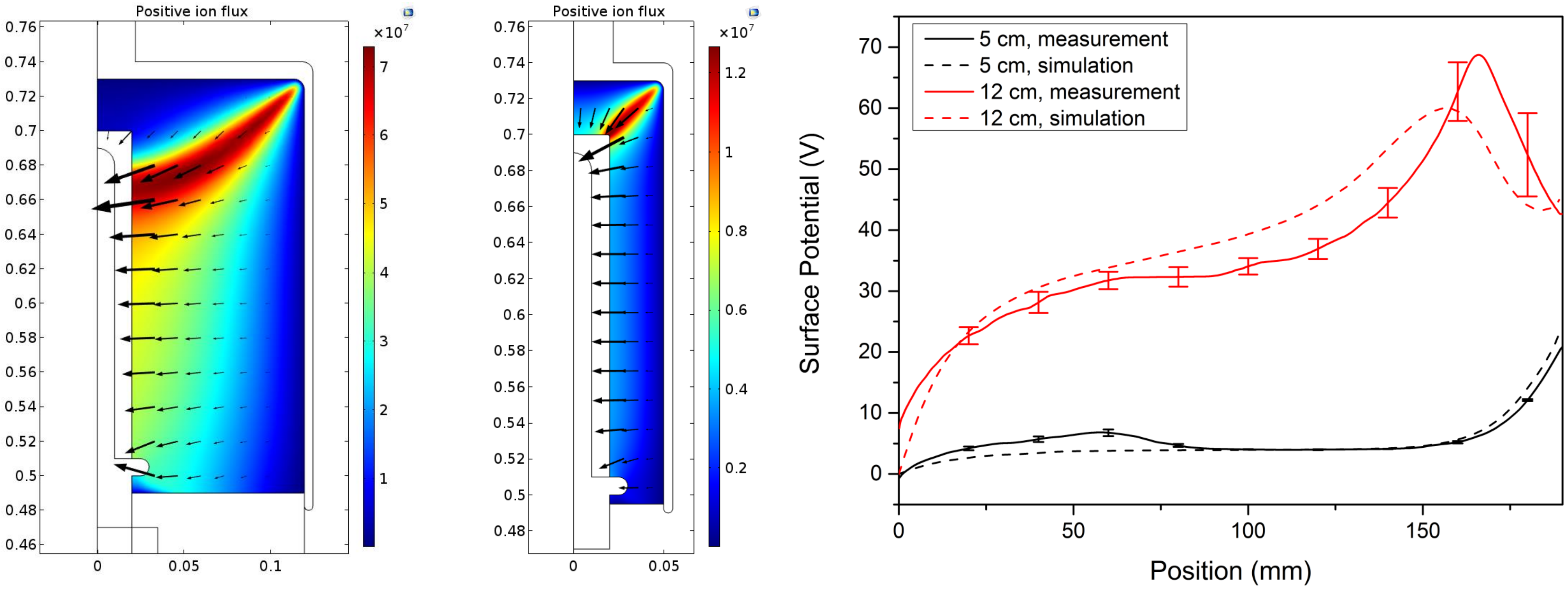




For comparison an RC model was applied to the full geometry including the gas. The gas resistivity was fit to data and despite using different values for the two geometries the fit is rather poor.

Data taken from M. Schueller and C.M. Franck, Influence of the Gas Volume Size on Spacer Charging in SF6 under DC Stress, *ISH* 2013.

Ion flow



The peaks in the experimental data can be related directly to the flow of positive ions in the gas. The flow is strongest about 20mm from the corner for the large electrode and near the corner for the small electrode.

Conclusions and outlook

- An ion drift model and an RC model were combined in COMSOL and applied to dielectrics composed of epoxy and SF6 under DC stress.
- A quasi-static approximation was introduced for the ion flow significantly speeding up the simulation and improving stability.
- The model reproduces experiments well with a fast and numerically stable implementation.
- The fit to data is poor for the pure RC model illustrating the importance of including ion flow in the gas.
- There are several possible extensions to the model that look promising.
  - Larger systems including air
  - Systems with dielectric liquids
  - 3D simulations

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