Numerical modelling of needle-grid electrodes for negative surface corona charging system

Y Zhuang, G Chen and M Rotaru
School of Electronics and Computer Science, University of Southampton, UK
E-mail: yz205@ecs.soton.ac.uk

Abstract. Surface potential decay measurement is a simple and low cost tool to examine electrical properties of insulation materials. During the corona charging stage, a needle-grid electrodes system is often used to achieve uniform charge distribution on the surface of the sample. In this paper, a model using COMSOL Multiphysics has been developed to simulate the gas discharge. A well-known hydrodynamic drift-diffusion model was used. The model consists of a set of continuity equations accounting for the movement, generation and loss of charge carriers (electrons, positive and negative ions) coupled with Poisson’s equation to take into account the effect of space and surface charges on the electric field. Four models with the grid electrode in different positions and several mesh sizes are compared with a model that only has the needle electrode. The results for impulse current and surface charge density on the sample clearly show the effect of the extra grid electrode with various positions.

1. Introduction
Over the years, considerable interest has been shown in the surface potential decay of corona charged polymeric materials. It is a simple and low cost tool used to examine electrical properties of dielectrics. The study of the potential decay in dielectric materials has a long history and is closely related to the wide application of corona charged dielectrics. It became a very popular topic after Ieda et al found the special cross-over phenomenon during surface potential decay in 1967 [1]. As a result many assumptions and hypothesis have been made to explain the phenomenon. There was also significant improvement in experimental equipment and environment. Baum et al [2] firstly introduced the needle-grid corona charging system shown in figure 1 and compared the surface charge density on the dielectric material with needle only corona charging system experimentally. Recently most of the corona charging systems are using the needle-grid set-up mainly for two reasons: firstly the surface potential of the dielectrics can be easily controlled by adjusting the magnitude of the grid electrode potential, and secondly the capability of this set-up to get a uniformly distributed charge density along the dielectric surface [3]. However, there is no work and available data on the potential differences and distance between the two electrodes such that a perfectly charged sample would be achieved. It has been found that there is no consistent data available to set-up up the grid position in relationship with both needle and sample. For example, in the literature available, the grid position is varied from 0.5 cm to 1.5 cm above the dielectric samples and the needle position is moved between 1 cm to 5 cm above the dielectrics [4, 5, 6].
The model in this work is based on a gas discharge model [7]. It was built in 2D axial symmetry configurations using the finite element COMSOL Multiphysics package. It has been proved that the negative corona discharge occurs in the vicinity of the cathode, therefore, due to the high electric field and charge densities, a very fine ‘FEA mesh’ need to be used around the needle head and along the axial symmetry line (figure 2). In this paper, the effect of adding the grid electrode to the corona charging system will be discussed by studying the impulse current formed and dielectrics surface charge density on sample surface.

Figure 1. Needle-Grid Electrodes Corona Charging System [8].

Figure 2. ‘FEA mesh’ distribution in the model.

2. Model Description

2.1. Geometry of the model

Figure 3. Corona Charging system simulation geometry.
From figure 3, it can be observed that the needle in our models has a curvature. The geometry of the needle is drawn with the help of equation (1). The radius of the curvature at the needle tip is 174 µm.

In the model shown on figure 2 the sample has a diameter of 28 mm and it is considered to be a polyethylene film with 50 µm thickness. In the first instance, the grid electrode is modelled as several concentric circular conductors, which are varied at different radiuses from the axial symmetry line of the model. The grid electrode has a thickness of about 500 µm; however in our model, this dimension is reduced to zero to limit the size of the ‘FEA mesh’, therefore reducing the computer memory. The bottom surface of the polyethylene sample is grounded and the needle electrode is fixed at 2 cm away from the ground. The grid electrode is set 0.5 cm or 1 cm away from the ground respectively. The model is solved using a transient solver within COMSOL. The electric potential of the needle and grid electrode are initially set to 0 V. Within the first 0.1 ns of the simulation these potentials are brought to the working voltage levels -6500 V for the needle and -1000 V for the grid respectively. From 0.1 ns to 5 µs when the simulation is stopped, the two voltage levels are kept constant.

2.2. Mathematical model

A well-known hydrodynamic drift-diffusion model consists of a set of continuity equations coupled with Poisson’s equation, given as:

\[
\frac{\partial N_e}{\partial t} = N_e \alpha [W_e - N_e \eta W_e - N_e N_p \beta_{ep} - \nabla \cdot (N_e W_e - D_e \nabla N_e)]
\]

\[
\frac{\partial N_p}{\partial t} = N_e \alpha [W_e - N_e N_p \beta_{ep} - N_n N_p \beta_{np} - \nabla \cdot (N_p W_p)]
\]

\[
\frac{\partial N_n}{\partial t} = N_e \eta [W_e - N_n N_p \beta_{np} - \nabla \cdot (N_n W_n)]
\]

\[
\nabla \cdot (\varepsilon_e \nabla V) + \frac{e}{\varepsilon_0} (N_p - N_e - N_n) = 0
\]

where \( t \) is time, \( e \) the electronic charge, \( \varepsilon_e \) the dielectric constant of free space, \( \varepsilon_r \) the relative permittivity and \( V \) the electric potential; subscripts \( e, p, n \) represent electrons, positive and negative ions respectively; \( N_e, N_p, N_n \) are the ion number density; \( W_e, W_p \) and \( W_n \) the electron, positive and negative ion drift velocities; \( \alpha, \eta, \beta \) and \( D \) the ionization, attachment, recombination and electron diffusion coefficients respectively. The simulation parameters in equations (2-5), which are functions of the local electric field, are given in table 1.

**Table 1. Simulation Parameters [7].**

| Parameters       | Functions                                                                 |
|------------------|---------------------------------------------------------------------------|
| \( \alpha \) (cm\(^{-1}\)) | 3500exp\((-1.65 \times 10^5 E^{-1})\)                                   |
| \( \eta \) (cm\(^{-1}\))    | 15exp\((-2.5 \times 10^4 E^{-1})\)                                      |
| \( \beta_{ep} = \beta_{np} \) (cm\(^3\)\(\)s\(^{-1}\)) | 2\times10^{-7}                                                           |
| \( W_e \) (cm s\(^{-1}\))     | -6060\(E^{0.75}\)                                                       |
| \( W_p \) (cm s\(^{-1}\))     | \(2.7 E\)                                                               |
| \( W_n \) (cm s\(^{-1}\))     | -2.7 \(E\)                                                              |
| \( D \) (cm\(^2\) s\(^{-1}\)) | 1800                                                                    |
The total current can be then computed using the energy conservation law:

\[ I = \frac{1}{V_{\text{needle}}} \left( \frac{d}{dt} \int_V W dV + \int_V P_D dV \right) \]  

(6)

where \( W = \frac{1}{2} \varepsilon_0 \varepsilon E^2 \) and \( P_D = E \times \sum eN_i W_i \).

The surface charge density can be calculated by integrating the normal component of charged particle current densities at the surface. In cylindrical coordinates, this can be expressed as

\[ \sigma_s(t) = \int_0^t (J_{ez} + J_{nz} - J_{pc}) dt \]  

(7)

where \( J_{le} = eW_{le} N_i \).

2.3. Boundary and initial conditions

The boundary conditions of all the models are shown in table 2.

**Table 2. Boundary Conditions for all the models.**

| Application mode | Convection and diffusion \( N_e \) | Convection and diffusion \( N_p \) | Electrostatics V |
|------------------|------------------------------------|------------------------------------|-----------------|
| Axial symmetry line | Axial symmetry | Axial symmetry | Axial symmetry |
| Needle electrode | Flux | Convective flux | Concentration=0 | \( V = -6500 \) |
| Grid electrode | Convective flux | Convective flux | Concentration=0 | \( V = -1000 \) |
| Polymer upper surface | Convective flux | Insulation/Symmetry | Convective flux | Surface charge |
| Open boundaries | Convective flux | Convective flux | Zero charge/Symmetry |
| Outer ground boundary | Convective flux | Concentration=0 | Convective flux | \( V = 0 \) |

At the needle electrode, the boundary condition for electrons is given as a secondary emission flux when positive ions strike the cathode

\[ N_e |W_e| = \gamma N_p |W_p| \]  

(8)

where \( \gamma \) has been used in the range from \( 10^{-2} \) to \( 10^{-3} \), it is chosen as 0.01 in this model [7].

The initial conditions are given as

\[ N_e = N_{\text{max}} \times \exp\left(-\frac{(r-r_o)^2}{2s_o^2} - \frac{(z-z_o)^2}{2s_o^2}\right) \]  

(9)

where \( N_{\text{max}} = 10^{15} \text{ m}^{-3}, \ r_o = 0 \mu m, \ z_o = 2 \text{ cm, } s_o = 25 \mu m; \ N_p = N_n = 0 \) [7].

3. Simulation Results

Five different models with or without the grid electrode were built as shown in table 3. Every model was run for 5 \( \mu \)s and the impulse current and surface charge density was observed. In this section a comparison of the obtained results is presented.
Table 3. Description of the Models.

| Model Number | Description |
|--------------|-------------|
| Model I      | Needle Only |
| Model II     | Grid electrode 5mm above the ground, mesh width is 5mm and gap width is 10mm. |
| Model III    | Grid electrode 10mm above the ground, mesh width is 5mm and gap width is 10mm. |
| Model IV     | Grid electrode 10mm above the ground, mesh width is 10mm and gap width is 10mm. |
| Model V      | Grid electrode 10mm above the ground, mesh width is 10mm and gap width is 5mm. |

3.1. Effect of the grid electrode height

In this section, the effect of the extra grid electrode with two different positions is compared with the model that has a needle electrode only. The results for models I, II and III are shown in figures 4 and 5.

![Figure 4. Current for models I, II and III.](image1)

![Figure 5. Surface charge densities for models I, II and III at 5 µs.](image2)

From the graphs above, it can be seen that the initial impulse current for model I and III shows at similar time, but it appears extremely late in model II. In contrast model III shows the existence of two impulse currents within 5 µs. Large differences in surface charge densities were observed. It can be noticed that at the point where the impulse current appeared, a great amount of electrons are generated as shown in figure 6. They will be pushed down to the sample surface, leading to an increase of surface charge density. As a result, model III has the largest surface charge density because of one more impulse current compared to the other two. It has been reported in [7] that the higher needle electrical potential will cause larger initial impulse current amplitude and a higher frequency of the Trichel pulse. In models II and III, the needle electrical potential is the same as in model I; however the impulse current is different. Therefore, the electric field underneath the cathode affects the behaviour of impulse current. From model I, it can be found that the electrical potential at 5 mm and 1 cm above the ground is about -600 V and -1200 V at the symmetry axis. The electrical potential at 5 mm above the ground is fixed to -1000 V in model II, therefore, reduces the electric field at the needle and leads to a smaller and slower first impulse current. In model III, the electrical potential is restricted to -1000 V at 1 cm above the ground, which leads to a higher electric field underneath the cathode and hence in this case a larger and faster first impulse current is observed.
3.2. Effect of the geometry of grid electrode

The real grid electrode is a fine mesh which varies in width and gap, which is different from the one built in current model. Therefore, three different geometries (model III, IV and V in table 3) of the grid electrode were selected and modelled to observe any possible effects of the mesh geometry to the surface charge density at the polymer. The results for these models are shown in figures 7 and 8. From those graphs, it is clear to see that the difference between the surface charge density is tiny. From these models, it can be noticed that at the beginning of the corona charging process, the electrons will travel from the cathode to the sample as model I; however with the infinitely thin grid electrode in the current models, the electrons can pass through the mesh and mainly through the gaps of the mesh. In figure 9, the logarithm plot of the electrons is shown at three different simulation times: 0.01 µs, 0.5 µs and 1 µs. It is clear to see that at the beginning of the simulation, a cloud of electrons sits underneath the needle electrode and then they were pushed towards the polymer; the process of how electrons passing through the grid electrode can be also observed clearly from 0.5 µs and 1 µs results. Therefore, it can be said that a 2D-axis symmetry model can be used with confidence to simulate corona charging process and it is much more efficient than a larger 3D model.
4. Conclusion

It can be concluded that by adding the grid electrode into the corona charging system the whole system will be affected. Varying the distances between the grid electrode and the ground will result in a different impulse current and therefore make the surface charge density difference. Our simulation results showed that the different grid electrode geometries do not affect much the current or the surface charge density at 5 µs. However, much longer solving time might be necessary to observe any possible effects of the grid electrode, and our model should be useful for such future observations.

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