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Streamer Propagation in a Point-to-Plane Geometry

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Introduction

When applying a high positive voltage to a sharp tip in atmospheric pressure gas, a positive corona sets in. In this corona a high number of electrons and positive ions are created due to impact ionization. Because of these collisions, photons are emitted and the region of highest ionization (few millimeters from the tip) can even be observed by the human eye. This region is called the ionization zone.

At sufficiently high electric fields, thin plasma channels (diameter in the order of 1 mm) of several millimeter length, called streamer, can occur.

Such a plasma channel is formed by a small region of high electron concentration (the streamer head) which travels towards the anode. In its trace the streamer head leaves a channel of positive ions, that form the actual plasma channel.

***GUNY**TRONIC* Gasflow Sensoric Systems develops a gasflow sensor based on ionization of the investigated gas by means of positive corona. A constant ion production rate is crucial for the sensor principle and therefore streamers are undesirable.

Several attempts to simulate streamer formation and propagation have been made in the past [1]. Kulikovsky used a hydrodynamic plasma model which he solved numerically using the finite difference method [2].

Here we present a way to solve a hydrodynamic plasma model by the finite element method using COMSOL Multiphysics.

Model Description

The modeled geometry is a so called point-to-plane geometry. In our case, a high voltage (10 kV) metal needle with a sharp tip (radius of curvature = 2.5 x 10^{-5} m) is in front of a grounded metal plate (20 mm x 1 mm). The distance between needle and metal plate is 20 mm.

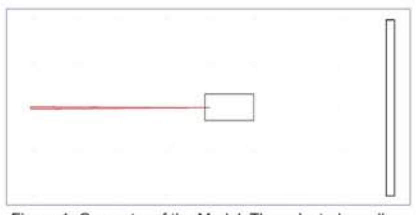

Figure 1: Geometry of the Model. The selected needle is the high voltage anode.

To model the formation and propagation of a streamer in air a hydrodynamic plasma model is used. This model describes the generation, annihilation and movement of three species (electrons, positive ions and negative ions), described by the following equations, which can be solved using the "Convection and Diffusion" Application mode [2]:

$$\frac{\partial n_e}{dt} + \nabla(-D_e \nabla \cdot n_e - \mu_e n_e \vec{E}) = S_{ph} + S_i - S_{att} - L_{ep}$$

$$\frac{\partial n_n}{dt} = S_{att} - L_{pn}$$

$$\frac{\partial n_p}{dt} = S_{ph} + S_i - L_{pn} - L_{ep}$$

Here: n_e, n_p and n_n denote the concentration of electrons, positive ions and negative ions, respectively. D_e is the diffusion coefficient of electrons and μ_e is the mobility of electrons. The mobility of ions is very low compared to that of electrons, therefore the ions mobility is set to zero.

L_{ep} (L_{pn}) describes the recombination rate of electrons and positive ions (positive and negative ions).

S_{att} is the rate of attachment of electrons to neutral molecules.

The electric field is determined using the Poisson equation, which is defined in the "Electrostatics" Application mode.

Results I:

Using the method described in the Box "Model Description" the concentrations of electrons, positive and negative ions are simulated. The formation and propagation of a streamer can be described best by the behavior of the electrons. Therefore, the presented results only show the electron concentration.

The behavior of a streamer can be divided into three different regimes, which will now be presented.

Streamer formation is initiated by assuming a small region of increased electron concentration (1 x 10^7 cm^{-3}).

The first 8 nanoseconds

In the first 8 nanoseconds the electron cloud travels towards the needle (due to the electric field of the needle which is at a high voltage of 10 kV).

Additionally, the electron cloud expands in radial direction due to diffusion and mutual electric repulsion of the electrons.

8 to 15 nanoseconds

Between 8 ns and 15 ns the electron concentration shows a new behavior: one can only observe the radial expansion of the electrons caused by their mutual repulsion.

The movement of the electron cloud towards the tip cannot be observed, because the electric field caused by the electron cloud itself is greater than the electric field of the needle.

Even though the maximum electron concentration is decreasing, the total number of electrons is increasing.

The third regime will be described in the box "Results II"

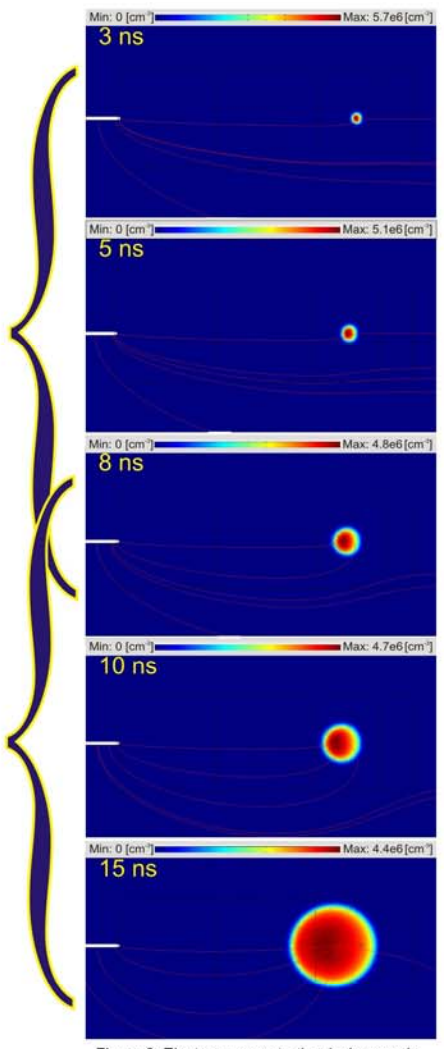

Figure 2: Electron concentration (color map in background) and electric field (red lines).

Results II:

15 to 18 nanoseconds

Between 15 and 18 ns the formation of a streamer shows a third regime. The electron concentration rapidly increases within a sickle shaped region at the side of the electron cloud facing the needle. This increase of the electron concentration is caused by photoionization.

The rate of photoionization is a function of the total electron concentration and increases with increasing electron number. After 15 ns the number of electrons is high enough and photo-ionization leads to an increase of the electron concentration. Since photoionization also depends on the magnitude of the electric field, the growth rate of electrons is greater in the vicinity of the tip.

This region of high electron concentration is the streamer head, which will be investigated in the next section.

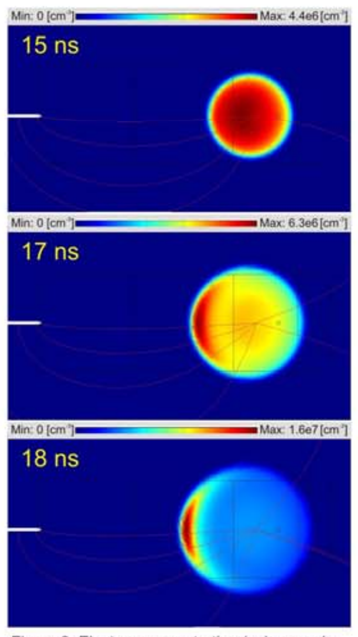

Figure 3: Electron concentration (color map in background) and electric field (red lines).

Investigation of the streamer head

Even though, the highest electron concentration (1.6 x 10^7 cm^{-3}) is in the streamer head, there is also a high number of electrons (5 x 10^6 cm^{-3}) in the trail of the streamer (blue contours).

The net space charge density shows a different behavior, which can be seen in the next figure.

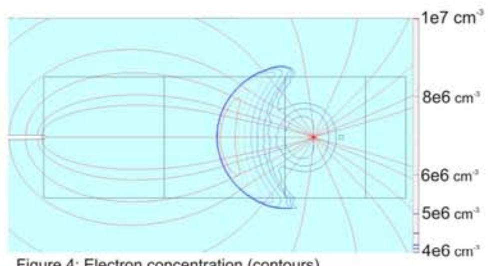

Figure 4: Electron concentration (contours) and electric field (red lines).

When looking at the space charge density, one can see that the only net charge is within the streamer head. This is because the charge of the electrons is compensated by the charge of positive ions, except in the streamer head where the number of electrons strongly exceeds the number of ions. This net space charge influences the electric field, which can also be seen in this figure.

A similar shape of the streamer head has been reported by others [3] [4].

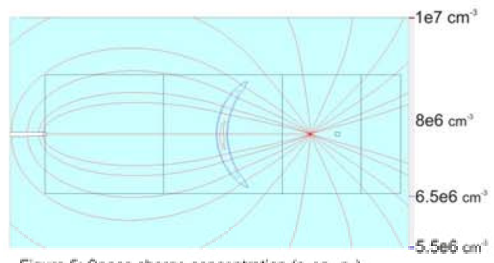

Figure 5: Space charge concentration (n_e+n_n-n_p) (contours) and electric field (red lines).

Conclusions

A hydrodynamic plasma model has been applied to simulate the generation and annihilation of three species (electrons, positive ions and negative ions) in an atmospheric pressure gas at high electric fields. Starting from an initial high electron concentration within a small area, three phases of the formation of a streamer could be shown. In the first regime, the electron cloud travels towards the positive potential of the metal tip. Additionally, the electron cloud expands, due to diffusion and mutual repulsion of electrons.

In a second regime the expansion is getting faster and the movement towards the tip can not be observed anymore.

In a third phase, a sickle shaped region of increased electron concentration is formed (due to photo-ionization). This region is the streamer head, which leaves a plasma channel in its trail while moving towards the high potential metal tip.

The model was fully implemented and solved with COMSOL Multiphysics using predefined application modes.

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GASFLOW SENSORIC SYSTEMS

The measurement of the flow of gases is a fundamental technique for the control of industrial processes. These measurements are managed with many different methods but nearly all of them have different limitations (i.e.: not suitable for: high temperatures, vibration and shock, particles,...) and additonally they often influence the measured medium.

The goal of ***GUNY**TRONIC* is to provide our customer with an universally applicable sensor system, without above mentioned limitations.

This can be achieved, since the ***GUNY**TRONIC* gasflow sensor is based on the particle nature of gaseous media. Therefore, external and internal influences by the measurement can be largely excluded.

References:

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