Streamer Propagation in a Point-to-Plane Geometry

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Abstract: Corona discharge is used in several applications such as surface treatment of polymers, photocopying or dust removal in air conditioning. Streamer formation is undesirable for most of these applications. Therefore, several studies have been dedicated to investigate the formation and propagation of streamers, which are still not fully understood.
The most suitable models to describe streamers are hydrodynamic models, which are usually solved using the finite difference method.
In this paper we present the successful simulation of the formation and propagation of a streamer. This simulation is based on a two-dimensional hydrodynamic plasma model which has been solved by the finite element method using COMSOL Multiphysics.

Keywords: Hydrodynamic model, Plasma Physics, Corona discharge, Streamer formation.

1. 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. The positive ions drift towards the cathode (i.e. away from the tip). Since these ions do not have enough energy for further ionization, no additional ions are created in the region between ionization zone and cathode, which is called drift 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 (i.e.: the streamer head) which travels towards the anode. In its trace the streamer head leaves a channel of positive ions, which form the actual plasma channel.

Gunytronic 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. Understanding the physics of streamer formation is therefore important for the development of this new sensor technology. Another paper on the physics of this sensor will be presented as oral presentation at the COMSOL Conference 2009.

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.

2 Governing equations

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 equations (1) to (3) [2]:

$$\frac{\partial n_e}{dt} + \nabla(-D_e \nabla \cdot n_e - \mu_e n_e \vec{E}) = S_{ph} + S_i - S_{att} - L_{ep} \quad (1)$$

$$\frac{\partial n_p}{dt} = S_{ph} + S_i - L_{pn} - L_{ep} \quad (2)$$

$$\frac{\partial n_n}{dt} = S_{att} - L_{pn} \quad (3)$$

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. $\vec{E}$ is the electrostatic field. S_{ph} and S_i describe the rate of generation of ions and electrons due to photo ionization and impact ionization, respectively. More details on S_{ph} can be found in appendix A.

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 mobility of ions is much lower than that of electrons, therefore ions are assumed to be immobile.
Expressions to evaluate the generation and annihilation rates in equations (1) to (3) can be found in [3]
The electric field is determined using the Poission equation:

$$\Delta V = -\frac{e}{\varepsilon_0}\left(n_p - n_e - n_n\right) \qquad (4)$$

where e is the magnitude of the charge of an electron.

3 Solving the model

3.1 Geometry of the model

The modeled geometry is a so called point-to-plane geometry. In our case a 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 shows the investigated geometry.

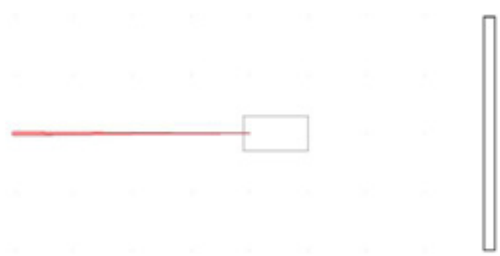

Figure 1. Model geometry of a 20 mm long needle (red) in front of a 20 mm broad metal plate (black bordered rectangle at the right). The grey bordered rectangle in front of the needle is a subdomain used for the simulation.

3.2 Numerical model

Equations (1) to (3) can be solved using the time dependent "Convection and Diffusion" Application Mode (chcd-mode) available in the Chemical Engineering Module, where n_p, n_e and n_n are the dependent variables. The generation and annihilation rates (e.g. S_i, L_{ep},…) can be entered in the Subdomain Settings of this application mode.
Only S_{ph}, the rate of photoionization, has to be treated in a different way, since it requires the integral of a function of n_e over the complete computational domain (see Appendix A). The evaluation of the original formulation of S_{ph} is very time consuming, therefore a simplified way to evaluate S_{ph} has been applied: the computational domain has been divided into several smaller domains and S_{ph} has been evaluated for a single point within such a subdomain using "Subdomain Integration Variables".
Equation (4) is defined in the "Electrostatics" Application Mode (es-mode).

The complete model was then solved step by step using the "Solver Manager". For the first time step (t = 0) an initial high electron concentration ($n_e = 10^7$ cm^{-3}) has been assumed in a small square (50 µm x 50 µm) 3.75 mm in front of the tip. This increased electron concentration is necessary to initiate a streamer. Such an increased electron concentration could be caused by e.g.: ionization by cosmic rays. Throughout the computational domain an initial concentration of n_p, n_e and n_n (10^3 cm^{-3}) is assumed. The needle has been set to a voltage of 10 kV. Then the es-mode is solved using these initial settings. This solution is stored and the first time step (1 ns) of the chcd-mode is solved using the stored electric field. The solution of the chcd-mode is now used as initial settings to calculate the electric field for the first time step (using es-mode). The solutions of the first time step (chcd-mode and es-mode) are now taken to solve the second time step (stepsize = 1 ns) of the chcd-mode. Figure 2 shows a block diagram of the solving procedure.

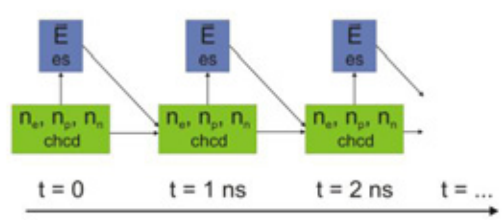

Figure 2. The solutions of the "Convection and Diffusion" Application Mode (chcd) and "Electro-static" Application Mode (es) of one time step are used to calculate the solution of chcd of the next time

step. To solve the es-mode, the solution of chcd of the same time step is used.

4. Results of the simulation

The procedure described in section 3.2 is applied to simulate the first 18 ns of streamer formation. Simulating the streamer formation is very time consuming, therefore, the chcd-mode is only solved in a small domain in front of the needle. This domain is shown as gray bordered rectangle in figure 1.

Figure 3 shows the initial situation of the model. One can see the initial high electron concentration in a small area in front of the needle (red rectangle). This additional charge has a small influence on the electric field, which can be seen on the shape of the electric field lines (red lines).

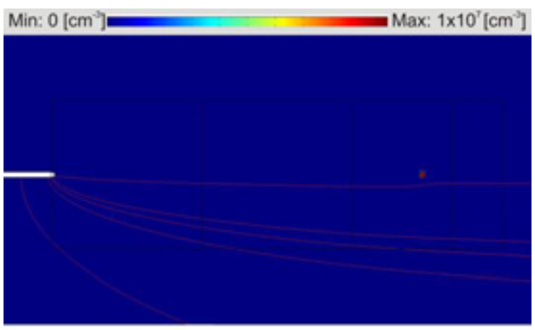

Figure 3. Illustration of the electron concentration at t = 0 ns. An increased electron concentration of 1 x 10^7 cm^{-3} is assumed in a small square in front of the needle (red square). Red lines represent electric field lines.

The formation and propagation of the streamer can be divided into three different regimes.

In the first 8 nanoseconds the electron cloud travels towards the needle (due to the electric field of the needle). Additionally, the electron cloud expands in radial direction due to diffusion and mutual electric repulsion of the electrons.

This behavior can be seen in figure 4 a, b and c, which show the electron concentration at t = 3 ns, 5 ns and 8 ns, respectively.

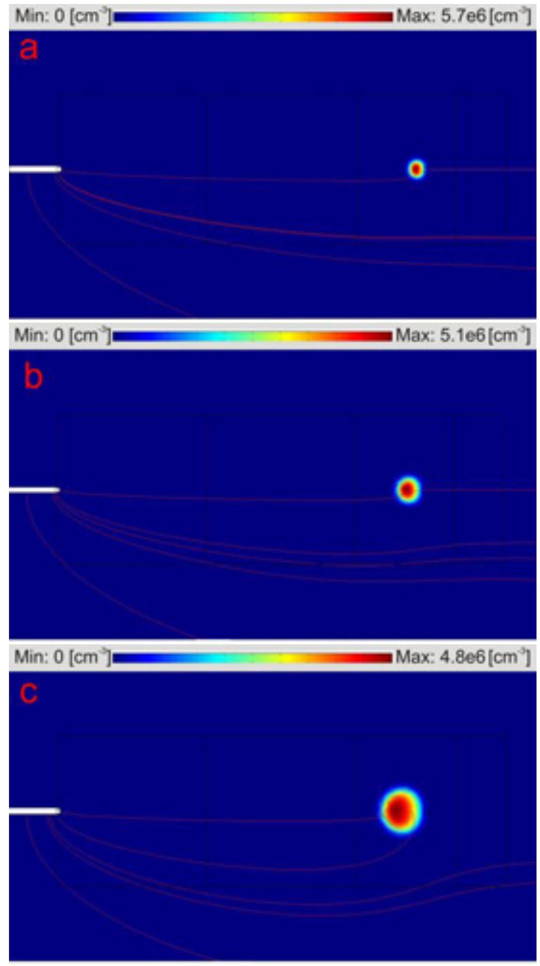

Figure 4. a, b, and c show the electron concentration at t = 3 ns, 5 ns and 8 ns, respectively. Red lines represent electric field lines.

In the second regime, which occurs between 8 ns and 15 ns, one can only observe the radial expansion of the electrons caused by mutual repulsion of electrons. 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. Figures 5 a,b and c show the electron concentration at t = 8 ns, 10 ns and 15 ns, respectively.

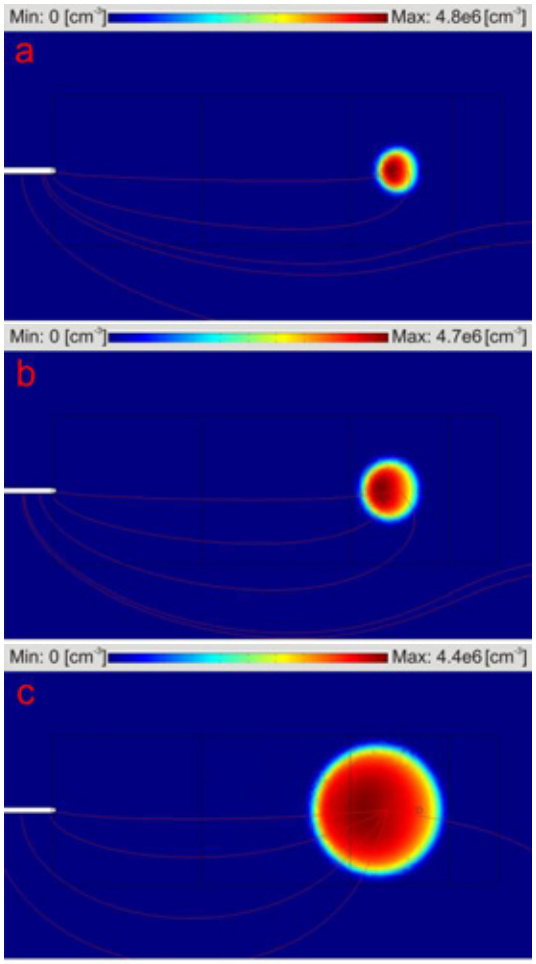

Figure 5. a, b, and c show the electron concentration at t = 8 ns, 10 ns and 15 ns, respectively. Red lines represent electric field lines.

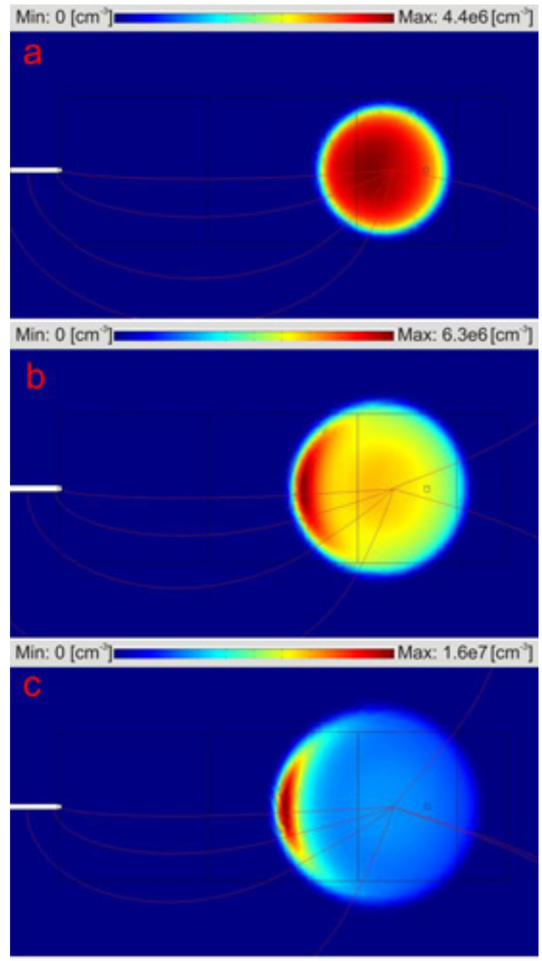

Figure 6. a, b, and c show the electron concentration at t = 15 ns, 17 ns and 18 ns, respectively. Red lines represent electric field lines.

After 15 ns the electron concentration shows another characteristic behavior: the electron concentration rapidly increases within a sickle shaped region at the side of the electron cloud facing the needle. This increase of n_n is caused by photoionization. As described in Appendix A, the rate of photoionization (S_{ph}) is a function of the total electron concentration and increases with increasing electron number. Between 0 and 15 ns the number of electrons is too little to cause a considerable amount of photoionization. After 15 ns the number of electrons is high enough and photoionization leads to an increase of the electron concentration. Since S_{ph} also depends on the magnitude of the electric field, photoionization is stronger in the vicinity of the tip.

This behavior can be seen in figure 6 a,b and c which show the electron concentration at t = 15 ns, 17 ns and 18 ns, respectively.
This region of high electron concentration is the streamer head, which travels towards the high voltage tip. A similar shape of the streamer head has been reported by others [4].

5. 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.
Starting from an initial high electron concentration within a small area, the formation of a streamer head could be shown.

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

6. References

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7. Appendix A: Calculation of the rate of photoionization S_{ph}

When electrons with high energy collide with neutral molecules, these molecules can be ionized (impact ionization), but also photons are emitted. These photons are the main source of photoionization described by S_{ph}.

Let's assume a point (x_1, y_1) in the computational domain. To evaluate S_{ph} one has to calculate the number of photons at (x_1, y_1).

The intensity of photon emission of a source area is [3]:

$$q(x_2, y_2) = A\alpha v_d n_e \qquad (5)$$

where: A ≈ 0,0038 is the ratio between emitted photons and the number of impact ionization events. $\boldsymbol{\alpha}$ is the Townsend ionization coefficient (cm^{-1}), v_d is the electron drift velocity (cm/s) and n_e is the electron concentration (cm^{-3}).

The photon intensity of a point source decreases with the square of the distance. Considering this, and the fact that photons are also absorbed, the number of photons at (x_1, y_1) emitted from an area at (x_2, y_2) is[3]:

$$P(x_1, y_1, x_2, y_2) = q(x_2, y_2)\frac{f(r_{12})}{r_{12}^2} \qquad (6)$$

where: r_{12} is the distance between (x_1,y_1) and (x_2,y_2) and f(r_{12}) describes the absorption of photons as a function of the distance.

In order to get S_{ph} at the point (x_1,y_1) one has to integrate over the complete computational domain[3]:

$$S_{ph}(x_1, y_1) = \iint P(x_1, y_1, x_2, y_2)\, dx_2 dy_2 \qquad (7)$$