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 axises 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 (low millimeters from the tip) can even be observed by the human eye. This region is called the ionization zone. When sufficiently high positive electric fields, thin streamer channels (thinner than the order of 1 mm) of neutral/ionic species connect the positive electrode (tip) to the negative electrode (plane).

Such a plasma channel is formed by a small region of high electron concentration (the streamer head) which moves towards the anode. In its trace the streamer head leaves a channel of positive ions, which form the plasma channel. GUNTRONIC Gasflow Sensory 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].

Kalužnov used a hydrodynamic plasma model which he tuned numerically using the finite difference method. Here we present a way to solve a hydrodynamic plasma model by the finite element method using FEniCS. Multiphysics.

Results I

15 to 18 nanoseconds

Between 15 and 18 ns the formation of a streamer shows a new regime. The electron concentration rapidly increases from a very low level at 13 ns to a peak level at 18 ns. The streamer head is thus growing and facing the needle. This increase of the electron concentration is caused by photionization. The rate of photionization 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 photionization leads to an increase of the electron concentration. Since photionization also depends on the magnitude of the electric field, the growth rate of electrons is greater in the front region of the streamer head. This region of high electron concentration is the streamer head, which will be investigated in the next section.

Investigation of the streamer head

Even though, the highest electron concentration (1 x 10^16 m^-3) is at the streamer head, there is also a high number of electrons (1 x 10^12 m^-3) in the tail of the streamer (blue contours). The net space charge density shows a different behavior, which can be seen in the next figure.

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 positive ions, which influences the electric field, which can also be seen in the next figure.

A similar shape of the streamer head has been reported by others [1-3].

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 expands towards the positive potential of the needle 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 cannot be observed anymore. In a third phase, a spherically shaped region of increased electron concentration is formed (due to photionization). This region is the streamer head, which leaves a plasma channel in its trail while moving towards the high potential needle tip. The presented model was fully implemented and solved with COMSOL Multiphysics using predefined application modes.

The measurement of the flow of gases is a fundamental technique for the control of industrial processes. These measurement 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 additionally they often influence the measured results.

The goal of GUNTRONIC is to provide our customer with an universally applicable sensor system. This can be achieved, since the GUNTRONIC gasflow sensor is based on the particle nature of gaseous media. Therefore, external and internal influences by the measurement can be largely excluded.

References:


Model Description

The modeled geometry is a so-called point-to-plane geometry. In our case, a high voltage (15 kV) is applied to a needle with a sharp tip (radius of curvature $2 \times 10^{-10}$ m) in front of a grounded metallic plane (20 mm x 1 mm).

The distance between needle and metal plate is 20 mm. 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 Modes.

For $\rho$ (where $\rho$ is electron density) an equation for the conservation of electrons, positive ions and negative ions is written:

$$\nabla \cdot (\rho \mathbf{u}) = \rho_i \mathbf{J}$$

where $\rho$ is electron density, $\rho_i$ is ion density, $\mathbf{u}$ is velocity, $\mathbf{J}$ is current density.

For $\mathbf{u}$ the continuity equation is written:

$$\nabla \cdot \mathbf{u} = 0$$

For $\mathbf{E}$ the electric field, the Poisson equation, which is defined in the “Electrostatics” Application Module.

The streamer forming is initiated by imposing a small region of increased electron concentration ($1 \times 10^{16}$ cm$^{-3}$).

The first 8 nanoseconds

In the first 8 nanoseconds the electron cloud expands towards the needle due to the electric field of the needle which is at a high voltage of 15 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”.

References: