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Streamer Discharge Initiation, Growth and Branching in a 3 cm Air Gap

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ABSTRACT

In this work, based on the stochastic model, streamer discharge was modeled and simulated within atmospheric pressure air gap. The plasma channels were followed, step by step, from the anode (rod) to the cathode (plane). That shows the streamer discharge bridges the air gap and indicates the minimum breakdown voltage required for a 3 cm atmospheric pressure air gaps as 27.56 kV. The streamer grows randomly in zigzag path and branched in several positions between the two electrodes. The number and positions of branches appeared depending on the applied voltage values. The electric potential and field distributions shown agreement with the streamer growth according to the simulation development time.

Keywords: Streamer discharge; Plasma channels; Air discharge; Pre-breakdown; Discharge simulation; Air gaps

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INTRODUCTION

In nature, the air is a dielectric material. When a sufficient potential applied on the air, it becomes conductor in form of streamer discharge. The streamer, which also known as filamentary discharge, can be formed when a sufficiently large electric field created by the applied voltage. The electric field accelerates electrons up to enough energy to strike air molecules and knocks other electrons. The new electrons, also, will accelerate and knock other electrons and so on. These electrons avalanches and an ionized region quickly grow near the electrode in direction towards other electrode forming a finger- like discharge called streamer. The streamer was considered as low- temperature non-equilibrium plasma usually takes form of streamer trees characterized by high electron and ion densities in a narrow channel [1,2]. Typically, the radius of a single streamer channel is of order of hundreds of micrometers and propagation velocity is in the range 10^5-10^7 cm/s [3]. The streamer theory considered by John Sealy Townsend from 1900 [4], but this theory sometimes inconsistent with observations. So that, a new type of discharge considered by Loeb and Raether in 1939 based on their experimental observations [5-7]. Also, Meek in 1940 presented the spark discharge theory [8]. This theory successfully explained the experimental observations. The low-temperature, non-equilibrium plasmas which produced by gas discharges in air have recently considerable attention. That is because of their capability in enhancement the reactivity of gas flows for many applications [9-12] such as ignition, ozone production, pollution control, disinfection, surface treatment, and soon. Due to practical needs, numerical simulations of streamers in air have interested significant attention during the last two decades. In this work, the streamer initiation, growth and branching will be simulated to show the behavior according to time development in 3 cm air gap within rod- plane electrodes configuration.

MODELING OF THE PROBLEM

The electrostatic field is the main parameter to determine the site of streamer initiation between the electrodes, so that Laplace equation must be solved within the region where the streamer accepted to initiate and growth (between the electrodes). The modeling, here, based one stochastic models, [13,14]. and follow the following considerations:

1. The simulation was implemented in the two dimensional square region of finite elements. Some nodes of some elements represent the electrodes, while the others represent the air between the electrodes.
2. The streamer initiate at the site (element) have an electric field value ≥ 26 kV/cm [15].
3. The streamer growths from step to the other spending a stochastic time τ can then be calculated from [15]:

$$\tau = -\ ^{ln(\delta)}/_{r(E)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where r(E) is a field depended growth rate function and given as:

$$r(E) = A\left[{}^{E_{log}}/_{U/d}\right]^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The parameter A is a constant with dimension of sec^{-1}, *n* is a number that controls the variation of the growth rate with the electric field, U is the applied potential at the anode and d is the gap distance. Parameter A can be calculated theoretically and during the simulations took the value $3.7 \times 10^5\ sec^{-1}$ [15].

4. The streamer channels are considered as a cylindrical weakly ionized plasma channels have high resistance, so that there is a drop voltage along it as 4.5 kV/cm [16].
5. The streamer pattern will branches into only two branches at certain condition. The condition was given as [17]:

$$MxQ \geq 2CrQ \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The parameter MxQ is defined as:

$$MxQ = max\int_0^x (\alpha - \eta)dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

And the parameter, CrQ is defined as the natural logarithm of the charge N_c at which the avalanche is able to convert itself to a streamer, and N_c given as:

$$N_c = \exp\left[\int_0^x (\alpha - \eta)dx\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where α is the Townsend's primary ionization coefficient and $\eta$is the coefficient of attachment; α is defined as the number of ionizing collisions caused by one electron while moving one centimeter in the direction of the electric field. Attachment of electrons is the process that leads to a depletion of electrons in the ionization region. Both these parameters are a functions of the reduced field E/N where N is particle density and were given by [18].

6. All the streamer branches were followed for one step only, because they usually will decay and only the main will bridge the gap between electrodes.
7. The electric potential of all element of the lattice that belongs to the air is calculated by solving the Laplace equation, for each streamer step, with the boundary conditions on the electrodes and the discharge pattern.

MODEL IMPLEMENTATION

The model to be implemented, a computer simulation must be executed within a suitable electrodes configuration. In this work, a rod-plane configuration was assumed as in Figure 1. The rod (anode) is of 10 cm length and 0.2 cm diameter. The plane (cathode) is of 13 cm diameter, and the distance between the electrodes is the air gap length of 3 cm. A positive DC high voltage was applied on the rod while the plane was grounded. Laplace's equation governs the voltage and electric field distributions within the configuration. So, finite element method (in two dimensions) was used as a good tool to solve Laplace's equation in the complicated configuration that requires the solution region to be discretized by a suitable mesh.

AUTO MESH 2D package was used to generate a mesh of 3398 elements and 1786 nodes for the solution region as in Figure 2. The mesh was designed to have high density elements around the head of the rod and low density far away because of the expected high variation of the voltage and the electric field around this region.

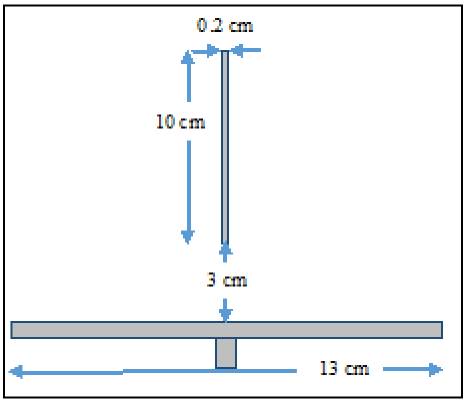

Figure 1: Longitudinal cross section for the electrodes configuration

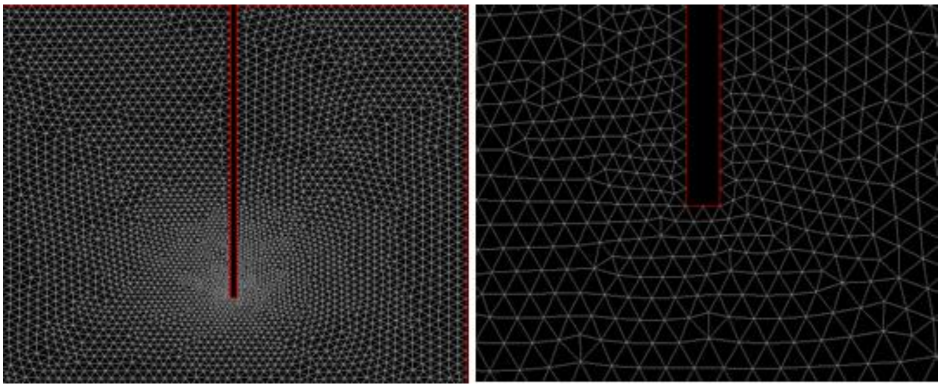

Figure 2: The discretization (mesh) for the solution region, a) The complete mesh for the solution region, b) enlargement of the region around the head of the rod electrode

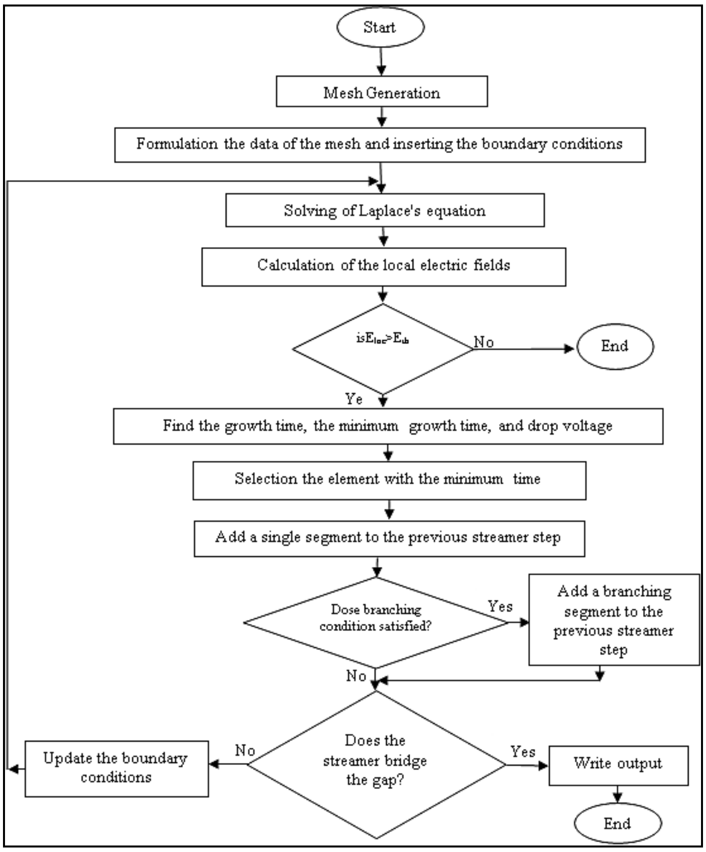

Figure 3: Flow chart for the computer simulation

All calculations that are required in testing the present model are done by a computer program. The program was written with Fortran 77 language. It was used to do the calculations that are needed to predict the voltage and electric field distributions within 3 cm air gap between the electrodes. As well as and to simulate the path and branching of the streamer within the simulation area. The procedure of the calculations is done as shown by the following block diagram (Figure 3).

RESULTS

The simulation was executed within the electrodes configuration of an air gap of 3 cm length to show the initiation and growth of the streamer from the anode (rod) to the cathode (plane). The first aim is to determine the breakdown voltage of this air gap and show the streamer branching.

Streamer Path between the Electrodes

The streamer initiation and growth will be tracked within the solution region between the two electrodes. According to the model, the streamer initiates at the elements that have electric field values greater than E_{th} (26 kV/cm). In the rod-plane configuration, the highest values are expected around the head of the rod and the growth with time is towards the plane.

The gap breakdown voltage was estimated at the minimum applied voltage value that grows streamer pattern to bridge the gap. The value for air gap of 3 cm in this work was obtained at 27.65 kV.

Figure 4 shows the streamer initiation and growth between the two electrodes for the minimum breakdown voltage. The figure shows, the initiation of the streamer at the head of the rod because of the highest values of the electric field. Also the streamer grows randomly but it stills under control by the electric field near the shortest distance between the two electrodes. It is found that the initiation time is 0.102 µs and the required time for the streamer growth to bridge the gap between the two electrodes and reach the plane is 4.34 µs.

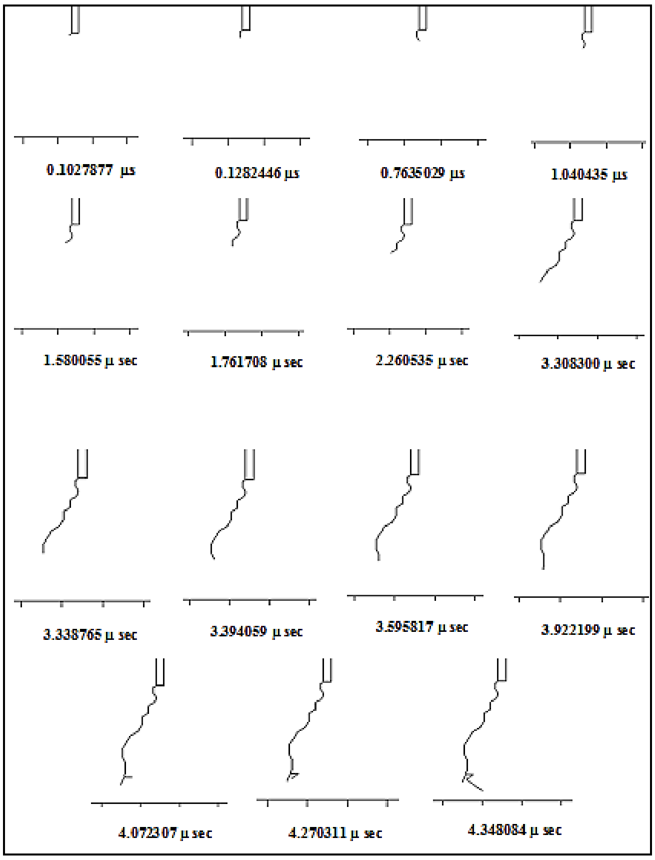

Figure 4: The time evolution of the streamer growth within a 3 cm air gap at breakdown voltage of 27.65 kV

Electric Potential and Field Distributions

The solution of Laplace's equation gives the voltage at every node on the mesh, in other word the potential distribution on the area of the longitudinal cross section of the electrodes configuration. These values of the voltages at the nodes of each element were used to calculate the electric field values at the center of each element. This will give the electric field distribution within the solution region.

Figures 5 and 6 shows an image plotting for the effect of the streamer growth on the distributions of the voltage, electric field magnitudes, at minimum breakdown voltage in the configuration. These figures indicate clearly the initiation and growth of the streamer according to the regions of the high values for potentials and fields. Also, one can observe, the streamer leaves behind regions with low values for the electric field because of the conductivity of its channels.

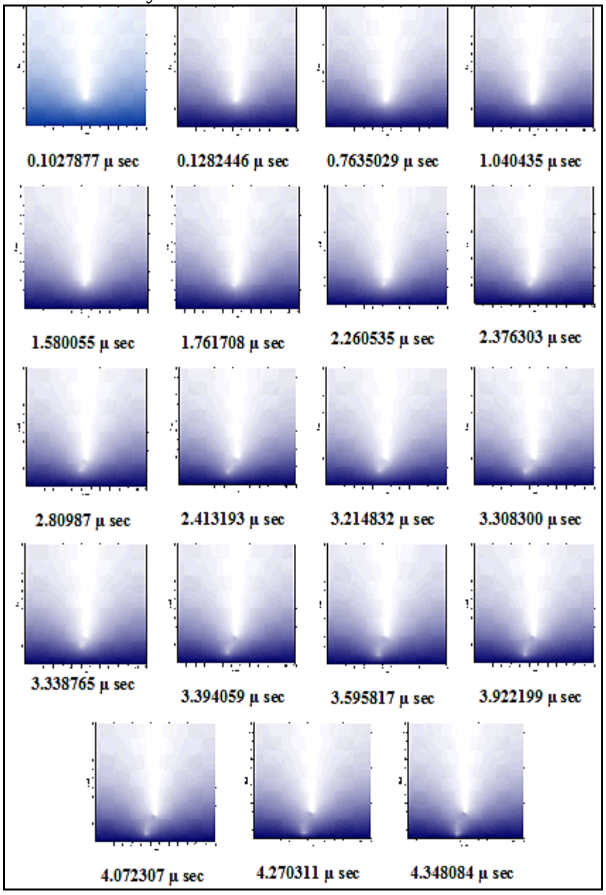

Figure 5: The time evolution of the potential distribution according to streamer growth within 3 cm air gap at breakdown voltage 27.65 kV

Streamer Branching

Streamer branching occurs when the condition in equation (3) satisfied. The calculation of this condition required the values of the coefficients of ionization (α) and attachment (η). These values of the reduced coefficients $\alpha/N$and η/N were calculated according to the reduced local electric field E/N at each of simulation steps and for different applied voltages as shown in Figure 7. From this figure, one can observe that the ionization processes is greater than attachment. Also, the ionization processes increases clearly with the increasing of the applied voltage. That is because of the increasing of the acceleration of the electrons and then their energies and cause more ionization processes. The streamer branching condition was implemented on the streamer at each step to indicate where the streamer branches. That was presented, for four values of applied voltages, in Figure 8. It was clear that the number of branches and their positions depend on the applied voltage value. That can be explained as the voltage increase the ionization increases too and the number of electrons which require for branching is satisfied.

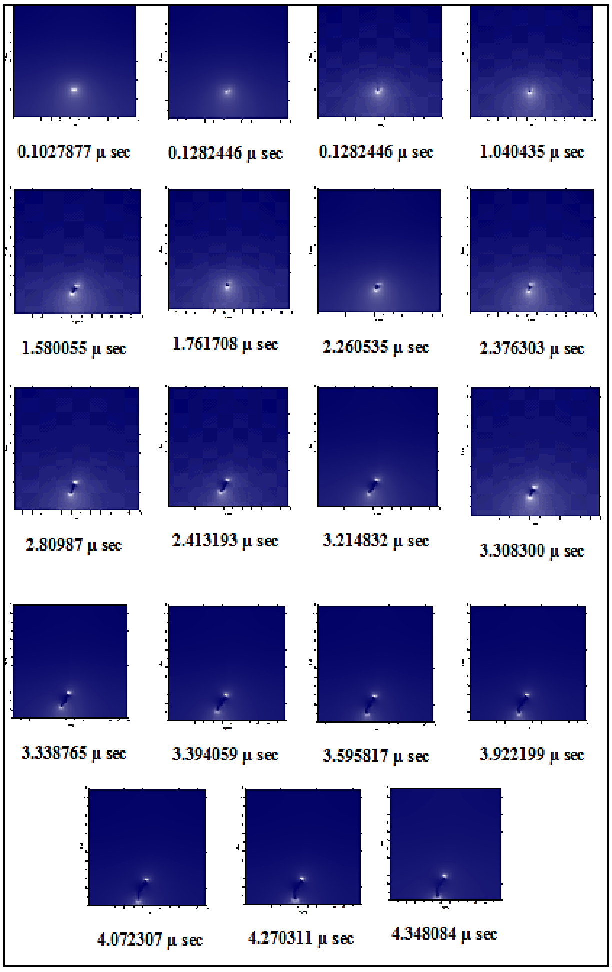

Figure 6: The time evolution of the electric field distribution according to streamer growth within 3 cm air gap at breakdown voltage 27.65 kV

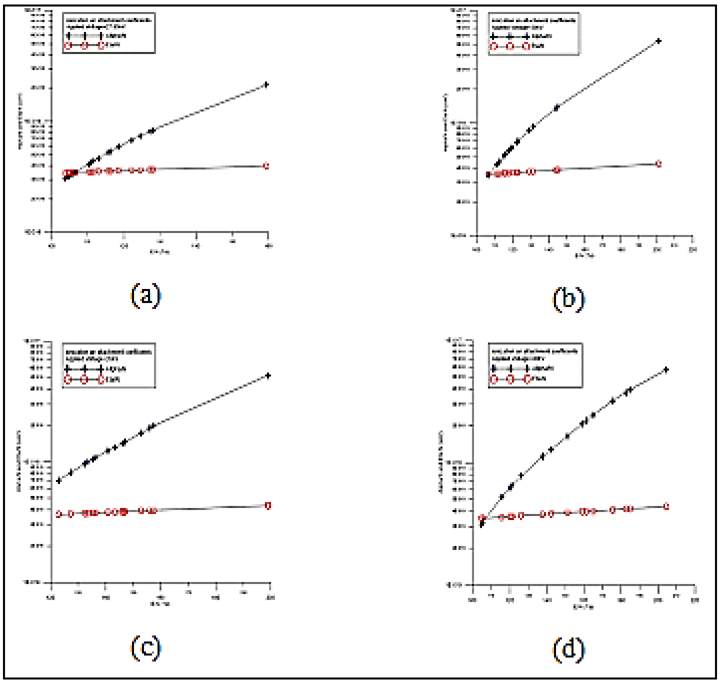

Figure 7: The reduced ionization and attachment coefficients as a function of the reduced electric field at each step of the streamer when the applied voltages of a) 27.65 kV, b) 30 kV, c) 35 kV, and d) 40 kV

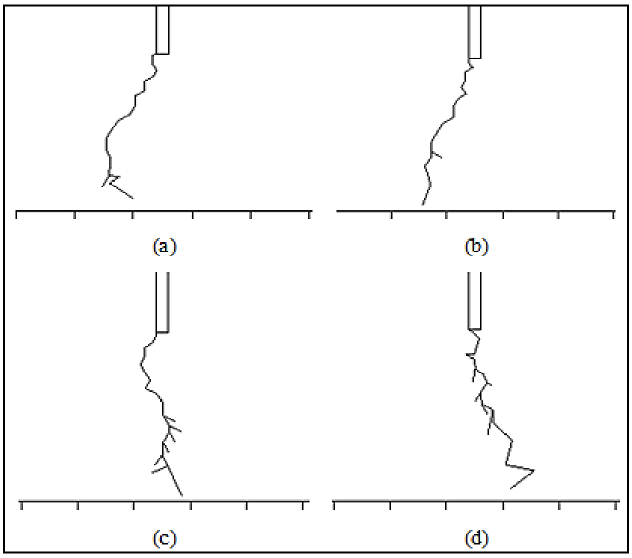

Figure 8: The streamer path and branching within the 3 cm air gap for different applied voltages of, a) 27.65 kV, b) 30 kV, c) 35 kV, and d) 40 kV

CONCLUSION

From the results that were obtained by the simulation, the following conclusions can be presented as below:

- The computational procedure, based on stochastic model, can give good results when compared with the experimental procedures.
- The initiation of the streamer at the tip of the rod because of the highest values of the electric field.
- The voltage and electric field distributions were affected by the streamer growth between the electrodes.
- The streamer grows randomly but, it stills under control by the electric field near the shortest distance between the two electrodes.
- The streamer moves according to the high voltage/E field regions from the rod down to the plane electrode leaved behind regions of low electric fields.
- The number of branches and their positions depend on the applied voltage values.

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