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Streamer Discharge Beginning, Development, and Branching in a 3cm Atmospheric Air Gap

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Abstract : In this work, based on the stochastic model, streamer discharge was modeled and simulated in an atmospheric pressure air gap of 3 cm length. The plasma channels (streamer discharge channels) were followed, step by step, from the anode (rod) to the cathode (plane).The streamer grows in random zigzag trajectory and branched in several positions between the two electrodes. The minimum applied voltage causes the streamer discharge to connection the air gap between the electrodes and causing breakdown is 27.46 kV. The number and positions of branches appeared depending on the applied voltage values. The local voltage and field distributions shown agreement with the streamer development trajectory conferring to the simulation progress time.
Keywords : streamer discharge, plasma channels, air discharge, pre-breakdown, discharge simulation, air gaps.

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. So that, near the electrode, an ionized region grows quickly and directly towards the second electrode in the form of finger- like discharge. That becomes well known as 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 sometimes this theory unreliable with remarks. So that, in 1939 Loeb and Raether considered a new type of discharge on their experimental remarks [5-7]. Also, in 1940 the spark discharge theory was presented by Meek [8]. The theory clarified successfully the experimental remarks.

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 twenty years. In this paper, the initiation, growth and branching of streamer discharge will be simulated to show the trajectory according to time steps development in a 3cm air gap at atmospheric pressure within a rod- plane electrodes configuration.

2. 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 in the region wherever the streamer is expected to initiate and growth (between the electrodes). The modeling, here, based one stochastic models, [13, 14], and depended the subsequent attentions:

1 **-** The simulation was executed in a two dimensional area of finite elements. Certain nodes of specific elements denote the electrodes, while the others denote the air between the two 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 which given by [15] as:

$$\tau = -\, {ln(\delta)}/{f(E)} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

Where $f(E)$ is a growth rate functiondepending on the field and seted as

$$f(E) = C\left[{E_{log}}/{V/d}\right]^{p} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (2)$$

The factor C is a constant has a dimension of sec^{-1}, p is a number which controls the variant of the growth rate with the electric field,V is the voltage that applied on the anode and d is the gap length. Factor C can be intended theoretically and acquired the value $3.7x10^{5}Sec^{-1}$[15]during this simulation.

4- The streamer channels are considered as a cylindrical weakly ionized plasma channels have high resistance, so that there is a drop voltage along itas 4.5 kV/cm [16].

5-The streamer pattern will branches into only two branches at certain condition. The condition was given as [17]

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

The parameter MxQ is defined as

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

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.

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

Where $\alpha$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, in the electric field direction, one centimeter. 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.

7- The voltage at all nodes of the area that have its place in the air must be calculated via resolving Laplace equation, at all streamer time steps, using boundary conditions on the two electrodes and the discharge trajectory.

3. 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 10cm length and 0.2 cm diameter. The plane (cathode) has a diameter of (13) cm, and the air gap length (between the electrodes) of 3 cm. A positive DC high voltage was applied on the rod while the plane was grounded.

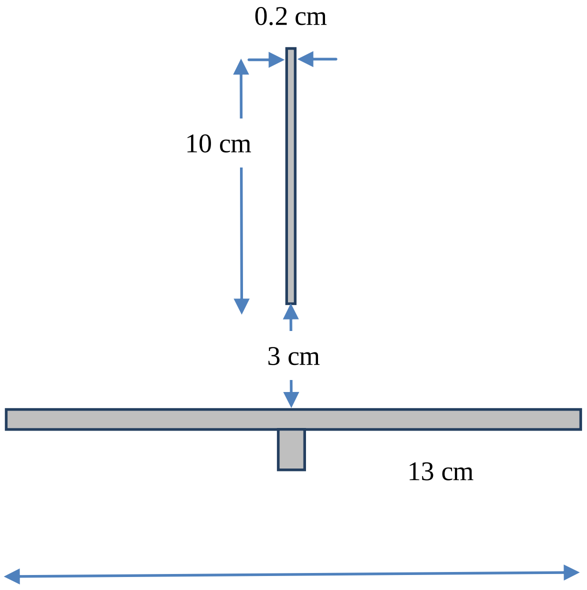
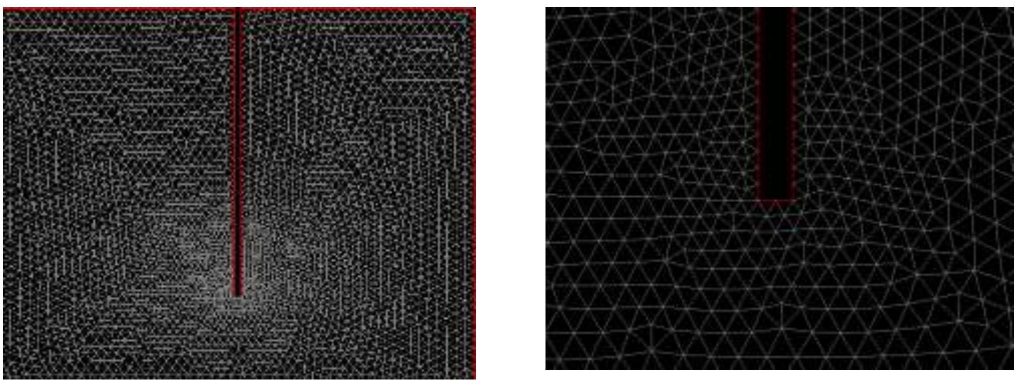


Figure (1): Longitual cross section for the electrodes configuration.

Laplace's equation manages 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 ameshof3398 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 values and the electric field values around this region.



(a) (b)

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.

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 required to calculate the voltage and electric field distributions within3cm 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).

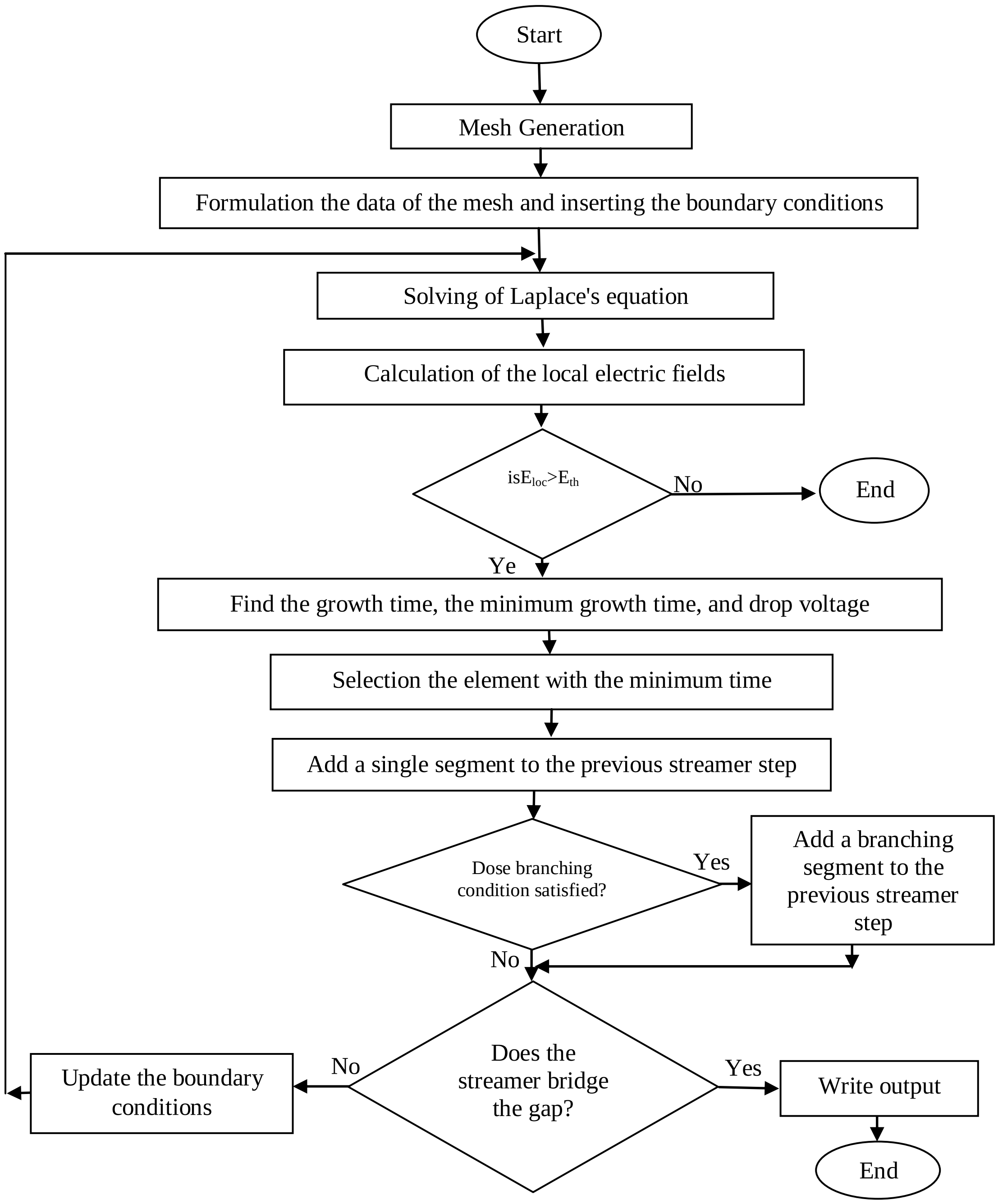


Figure (3): Flow chart for the computer simulation.

4. The Results

The simulation was executed within the air gap between the electrodes. That was done to show the initiation and growth behavior of the streamer from the rod (anode) to the plane (cathode). That is firstly to determine the minimum breakdown voltage of this air gap and show the streamer branching.

4. 1 Streamer Trajectory between the Electrodes

The streamer beginning and development will be tracked in the air gap between the two electrodes. Conferring to the model, the streamer starts at the elements that have electric field values larger than E_{th} (26kV/cm). The maximum values, in the rod-plane arrangement, are expected near the head of the rod and the development with time is in the direction of the plane.

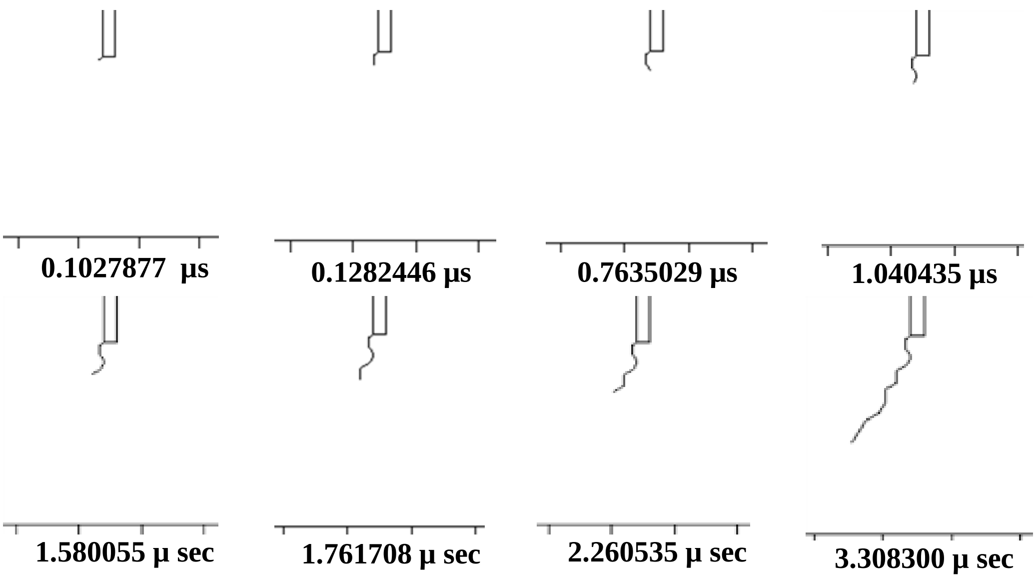
The air gap breakdown voltage value was determined as the minimum applied voltage value that causes the streamer trajectory to connection the gap electrodes. The value for air gap of 3cm in this paper was obtained to be27.65 kV.

Figure (4) appearances the streamer beginning and development between the two electrodes for the minimum breakdown voltage value. It was observed, the beginning of the streamer near the head of the rod because of the maximum value of the electric field. Also the streamer propagates randomly but it stills under governor of the electric field nearby the direct distance between the two electrodes. It is found that the beginning time is 0.102 µs and the required time for the streamer development to connection the gap and touch the plane is 4.34 µs.

4.2 The Local Voltage and Electric Field Distributions

The Laplace equation solutionprovides the voltage at each node in the meshin the area of the longitudinal cross section of the electrodes arrangement.These values were used to compute the local electric field values at the center of each element. This will give the local electric field distribution on the solution area.

Figures (5) and (6) display an image plotting for the influence of the streamer development on the distributions of the local voltage and electric field values, at the minimum breakdown voltage in the arrangement. These images specify noticeably the beginning and development of the streamer conferring to the sites for the highest values of voltages and local fields. Also, one can notice the streamer plants behind trajectory with low values for the electric field because of the conductivity of its plasma channels.



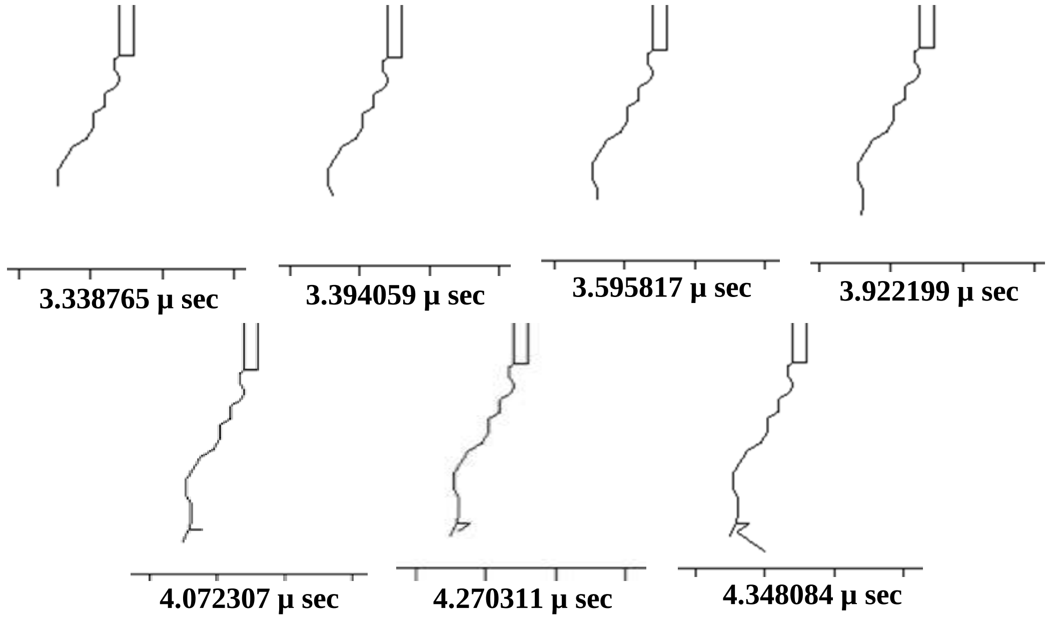
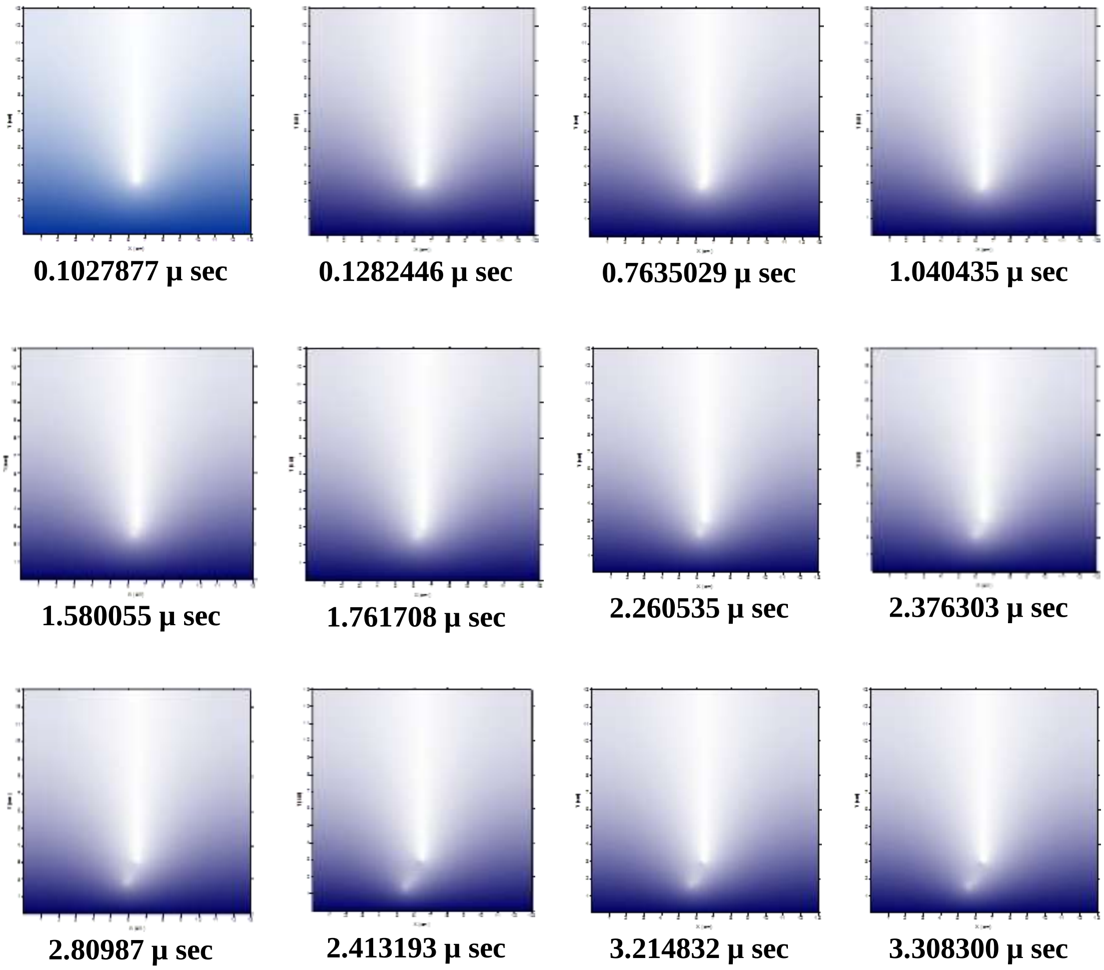
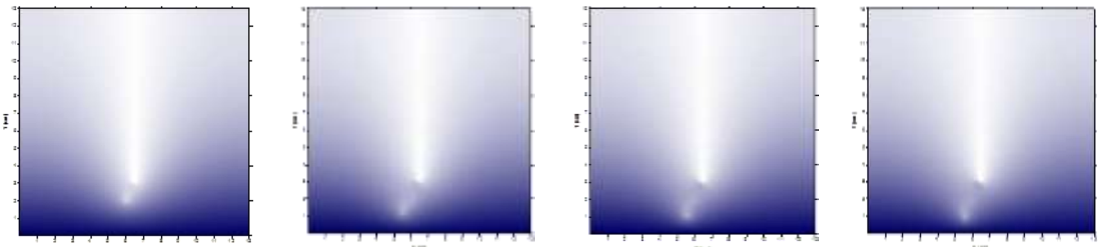
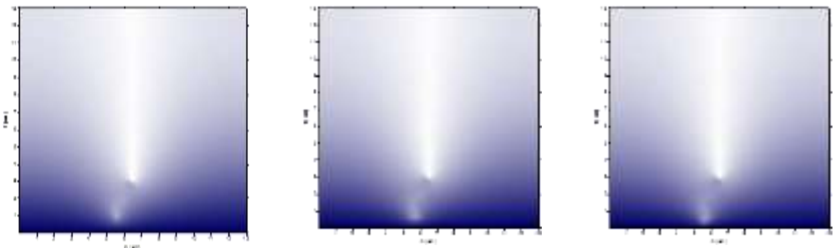


Figure (4): The time progress of the streamer development in the 3cm air gap at the minimum breakdown voltage of 27.65 kV.



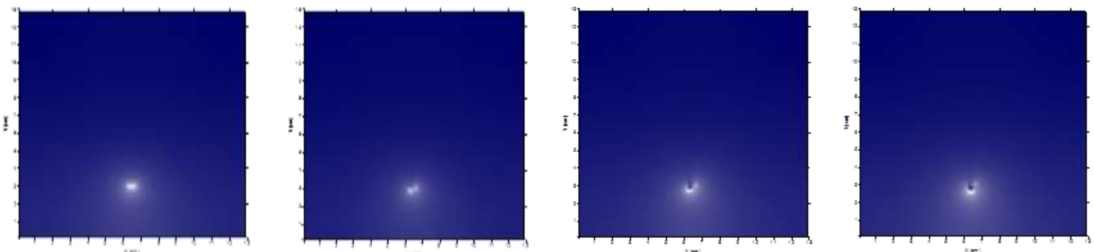


3.338765 µ sec **3.394059 µ sec** **3.595817 µ sec** **3.922199 µ sec**

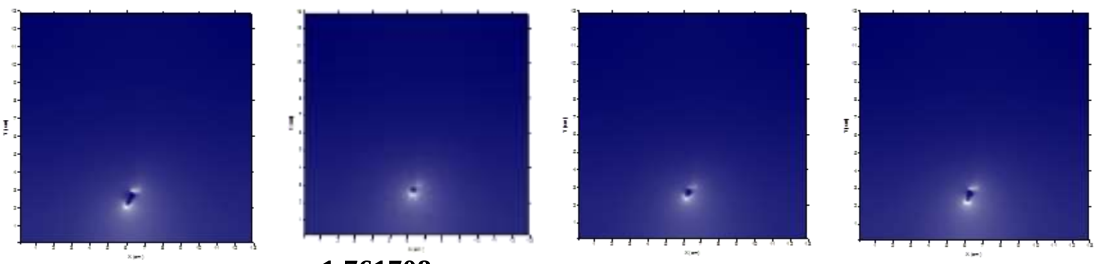


4.072307 µ sec **4.270311 µ sec** **4.348084 µ sec**

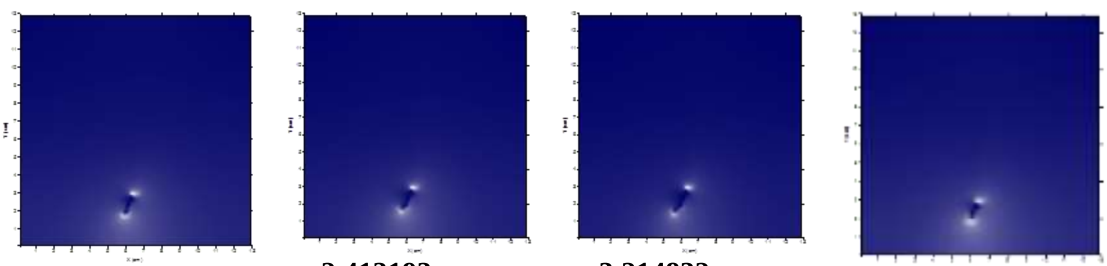
Figure (5):The time progress of the local voltage distribution allowing streamer development in the 3 cm air gap at the minimum breakdown voltage 27.65kV.



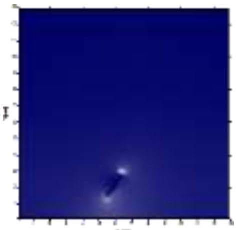
0.1027877 µ sec **0.1282446 µ sec** **0.1282446 µ sec** **1.040435 µ sec**

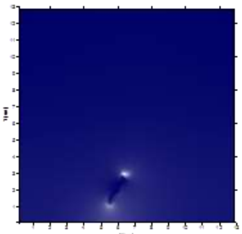


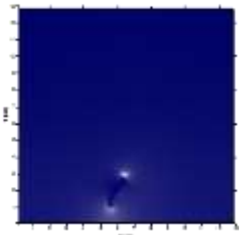
1.580055 µ sec **1.761708 µ sec** **2.260535 µ sec** **2.376303 µ sec**

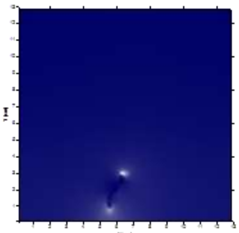


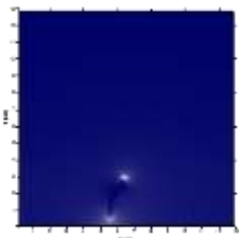
2.80987 µ sec **2.413193 µ sec** **3.214832 µ sec** **3.308300 µ sec**

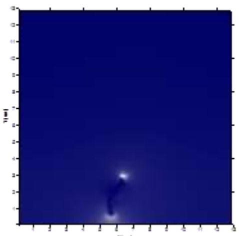

3.338765 μ sec


3.394059 μ sec


3.595817 μ sec


3.922199 μ sec


4.072307 μ sec


4.270311 μ sec

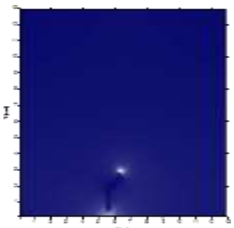
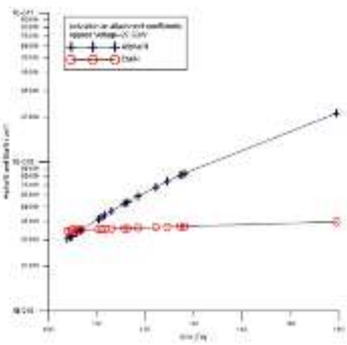

4.348084 μ sec

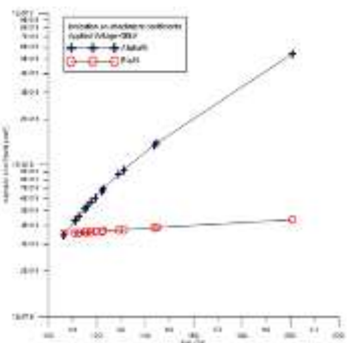
Figure (6):The time progress of the local electric field distribution allowing streamer development in the 3 cm air gap at the minimum breakdown voltage 27.65kV.

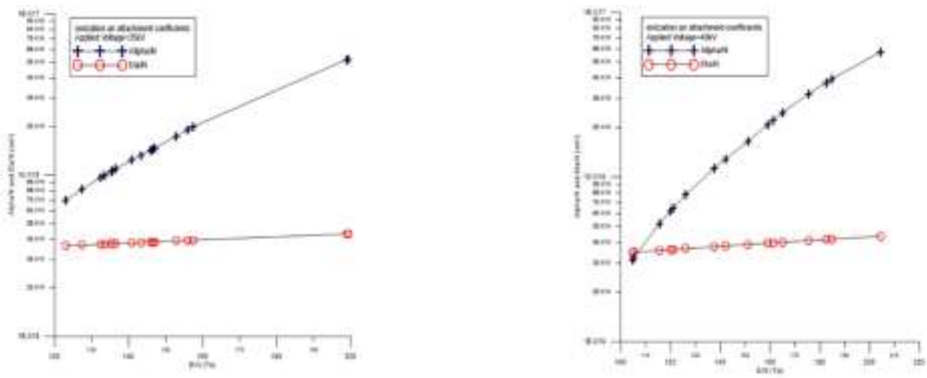
4.3 Streamer Branching

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 noticeably according to the increasing of the applied voltage.

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 that required for branching is satisfied.

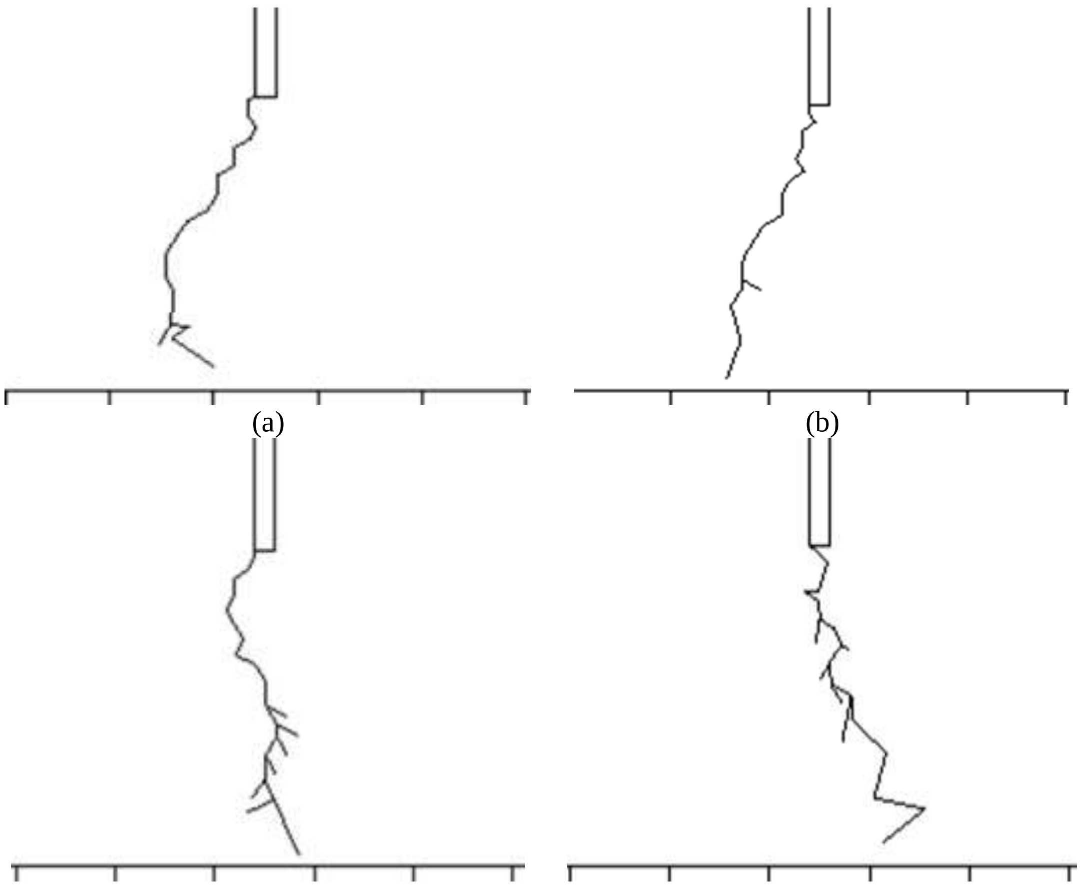

(a)


(b)



(c) (d)

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.



(a) (b) (c) (d)

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

5. Conclusions

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

- The computer simulation, based on stochastic model, can provide respectable results.
- The beginning of the streamer at the tip of the rod because of the maximum values of the local electric field.
- The local voltage and electric field distributions were influenced by the streamer development between the two electrodes.

- The streamer propagates randomly but, it stills under governor of the local electric field values near the direct distance between the two electrodes.
- The streamer propagates conferring to the high local voltage/E field values from the anode down to the cathode plants behind trajectory of regions with low local electric field values.
- The number of branches and their positions depend on the applied voltage values.

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