Simulation and Study the Effect of the Channel Radius Streamer Discharge Propagation, and Characteristics in Water Filled Gap

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Abstract

In this work; based on the bubble theory, streamer discharge has been modeled and simulated in the water gap of 2.75mm length under the action atmospheric pressure. The streamer channels (plasma) were followed, at each time step. The simulation leads to the observation of growth, and branching of streamer channels between the two electrodes (pin – plane configuration). The results show that, the growth, and branching is dependent on the electric field distribution with the solution region. The streamer brides the water gap from anode (point) to cathode (plane) at a voltage of 17 kV. Also, increase the number of branches with the approaching to the cathode (plane). That indicates the streamer velocity increased with increasing the streamer time development. Generally, all values of the streamer characteristics increase with the increasing radius of the streamer channel except the decrease of degree of ionization with an increase in the radius of the streamer channel.

Key Words: Bubble Theory, Channel Radius, Streamer Theory.

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Introduction

Insulating fluids like the transformer oils, water and liquid Nitrogen etc... Are considered as vital components in the high voltage and power devices. Researches on conduction in the liquid dielectrics, particularly water, started several years ago due to its significance for applications like the insulators. Others [1-3] carried out researches of the impacts of the contamination, age, and gas content on the general quality of water, which affects the mechanisms of the breakdown and conduction. The characterization of liquids' breakdown is significant to optimize material utilization. The identification of the modes of failure or the critical situations which are required for the fail of a liquid is important to understand the way the breakdown is going to progress. A successful model for mechanisms which take place in the liquid breakdown, which is involved with a unique complexity level, in comparison with the dielectric breakdown of solids or gases. The streamers' breakdown is dependent on the electric field distribution in inter-electrode gap. For the non-uniform field, in other words, the point-plane gap, the breakdown is dominated by streamer propagation [4,5].

There are many theories that expound the mechanism of streamer, such as electronic theory, ionization theory, electro-thermal theory and bubble theory. The last one is the base of modeling in this work [6-9].

The theory that a cavitation or the bubble process may cause a breakdown in dielectric liquid was proposed.

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Krasucki [10]. With progressing of the high speed approaches of imaging, the streamer (i.e. the bubble) theory has been put forward for explaining the procedures of the breakdown in the insulating liquids. With the development of high speed imaging techniques, the bubble theory was put forward to explain the breakdown processes in insulating liquids. This theory was first developed in the early 1970s [10]. The earliest form of this theory was also called 'streamer theory', which came from the gas bubble observation before a breakdown occurs. A detailed study of the influence of thermal bubbles was summarized by Hayakawa [11]. Sharbaugh and Watson [12] proposed a thermal mechanism for breakdown. They indicate that there is a large current density and high local field and that the energy input to liquid may lead to vapor bubble formation in a few microseconds. According to Krasucki [10] and Thomas [13] he added several terms to Krasucki's mathematical equation of bubble growth. The model shows good agreement with experiments when considering the dependence on pressure and temperature. Chadband and Wright [14] suggested that the cavity region (the bubble) might be ionized plasma.
As a result of the workable needs, numerical streamer simulations in insulating water gained a lot of interest throughout the past 20 years. In the present paper, the initiation, growth and branching of the streamer is going to be simulated for showing the behavior based on the time growth in the 2.75mm water gap within pin-plane electrode configuration.

The Modeling

The model includes the simulation of multi-channel streamer propagations fundamentally based on the bubble theory. This model, here, was built based on several assumptions to initiation the growth of a streamer within the buffer liquid. Therefore, the proposed model depended on the merge of the basic concepts of the bubble theory. Many conditions have suggested to the start and growth of the streamer. The possibility of initiation and development of a streamer can be satisfied when

i. The local electric field (E_{loc}), the electric field at the streamer tip (E_{tip}) and electric field inside the bubble (E_{bub}) are higher compared to the threshold electric field [15], required for initiating one of the various streamer types (primary, secondary or tertiary streamers based on classifications as a result of Badent et al [16] or 1st, 2nd, 3rd and 4th modes based on Hebner [17]); which may be computed at [15,18].
ii. The energy (W_{jou}) which is provided by the electric field has to be greater compared to Latent heat of liquid vaporization.

The Simulation

For the sake of validating our model, consider a tip - plane electrode geometry, submerged in an insulating (transformer oil) of the permittivity is (2.2), and the conductivity of channel = 0.1S.m^{-1}. The model which will be implemented, a computer simulation has to be executed in a point-plane electrode configuration, figure (1). The point (anode) is of 10mm length. The plane (cathode) is about (2.75) mm diameter, and the distance between the electrodes is the liquid gap length of 5mm. A positive DC high voltage has been applied to the tip (V_0= 17 kV) while the plane was grounded.

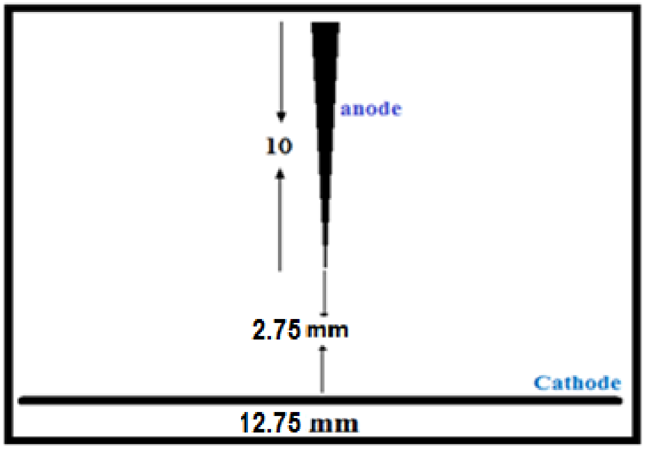
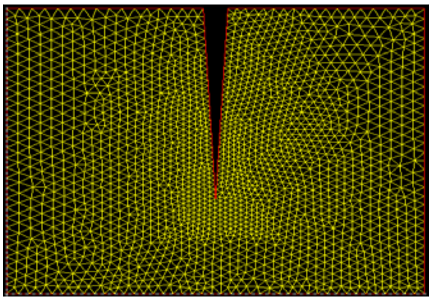
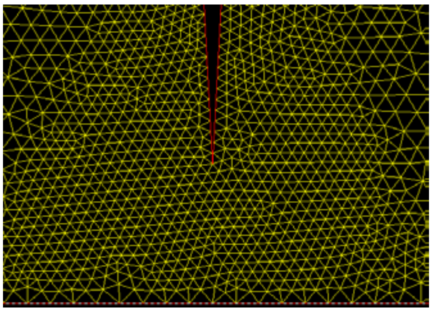


Figure 1. Longitudinal cross section of point - plane configuration.

The AUTO MESH 2D package has been utilized for the generation of a mesh of 4,026 elements and 2,119 nodes in the region of the solution as in fig2. This mesh has been designed for having elements of high density surrounding the point's tip and low density in farther distance as a result of projected high voltage variation and electric field which surrounds this area. The equation of Laplace regulates electric field and voltage distributions in the configuration. Which is why, the approach of the finite element (in 2-D) has been utilized as an efficient tool for solving the Laplacian equation in the complex configurations; with the use of program (Simple 2D) [19,20, 21]. Which needs for the region of the solution to be discretized by a proper mesh.



(a)



(b)

Figure 2. The grid for the point – plane configuration, a) a complete grid for the longitudinal cross section of the configuration, b) enlargement of the area which surrounds the tip of point electrode.

All the computations which are required to test this model have been carried out using a computer program, which has been written with Fortran77 language. It has been utilized for performing calculations which are required for the prediction of the distributions of the electric field and the voltage in the water gap between electrodes. In addition to the simulation of the path and branching of the streamer in the area of the simulation.

The Results

The simulation has been executed in the configuration of the electrode of a liquid gap of 2.75mm length for showing the streamer's initiation and growth from anode (point) to cathode (plane). The fundamental aim of this research is to study the effect of increasing radius of the streamer channel on the streamer propagation, and some Characteristics streamer.

The Conditions of Streamer Initiation and Growth in liquid

The simulation results show that all assumed conditions are met at each run step. Each result was represented using the Originpro8 program and represented by a vertical drop line because all measurements were taken at a specified time in each run and each time step.

The Electric Field at the Streamer Head

The electric field (E_{tip}) at the streamer tip or head as a result of the space charge in the area which is known as active region. This electric field depends on the voltage on the steamer tip, streamer radius and the remained distance between streamer tip and plane electrode. In the case of performing the calculations with the streamers, it's beneficial modelling the tip of the electrode as rotational hyper-boloid. Then, the equation of Laplace is separable and may be solved in the coordinates of the prolate spheroid [22]. Also, it was calculated using equation.

$$E_{tip} = 2\Delta V/(r_0 \ln 4(D - l_c/r_0) \quad (1)$$

Where ΔV is the drop voltage, D is the gap length and lc is the streamer channel length.

Figure (3) shows the simulation program results and development of the primary and secondary streamers. Also, show the electric field values decreases with time until oncoming at the state of electrical breakdown because of voltage drop and decrease the distance between the poles in every step of the time. The strong electric field leads to directly ionizing the liquids.

The simulation results show that increasing the radius of the channel streamer is inversely proportional to the electric field values. When comparing simulation results with research, we observe broad agreement with experimental and theoretical research by studying the flow development in dielectric fluid [23,24,25].

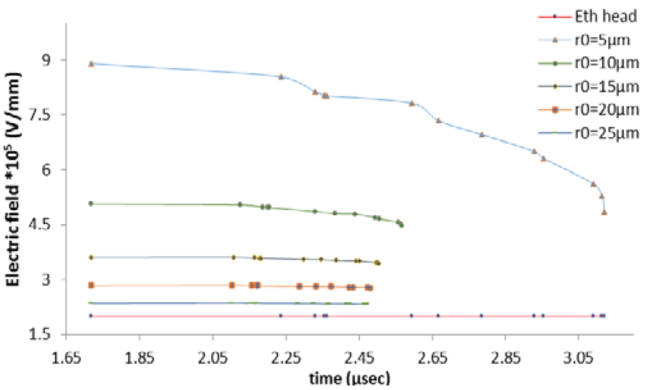


Figure 3. The E_{tip} at every step of the streamer time progression with different the radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

The Electric Field inside Bubble

It will allow the streamer to grow every step to show the value of the electric field ($E_{bub.}$) of the streamer. Previously it was assumed that the streamer couldn't propagate when the value of the ($E_{bub.}$) is less than 10kV/mm. It is introduced to the streamer growth model by using the Onsager field model, which is given by [26]

$$\vec{E}_{bub} = \frac{3\varepsilon_r}{2\varepsilon_r + 1}\vec{E}_{loc.} \quad (2)$$

It was suggested that the range of the bubble radius generated inside the liquid is between 5 and 25 µm. The bubble 20 µm radius was examined in this work.

Figure (4) shows the electric field ($E_{bub.}$) values at each step of the streamer time development of gap length 2.75mm. The values of the electric field have been computed with the use of equation (2).

Figure (4) illustrates the value of the electric field increases with the growth time of the flow of one case. The same behavior, the values of the electric field increase with increasing the radius of the channel streamer. An increase in the electric field value is due to its dependence on the local electric field electric field. When comparing the results of the simulation with research, he observed that the behavior was closely matched with experimental and theoretical research on the study of diffusion and growth in dielectric fluid. [27,28]

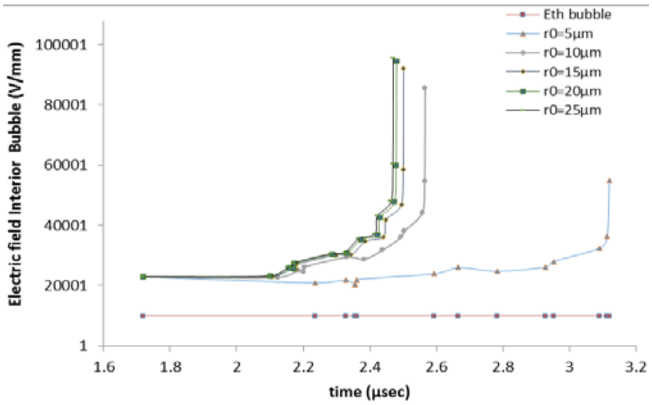


Figure 4. The E_{bub} at every one of the steps of the streamer time development with different the radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

The Effect of the radius channel on Propagation and Branching Streamer

The streamer initiation and growth was traced in the region of the solution between the 2 electrodes. A streamer is initiated at the elements that have values that agreement with the conditions [17, 18].

The gap breakdown voltage has been estimated at minimal value of the applied voltage which grows the pattern of the streamer to bridge the gap [17, 18].

The initiated streamer grows and branches toward all elements that satisfy the four conditions. Then, all branches were stopped at the first step except the main one at the element which has the highest electric field value. This one will grow to the next step.

The simulation was repeated at the same conditions, but with different the radius channel (5, 10, 15, 20, and 25 mm). That is to show the effect of radius channel on the streamer branching as in figures (5).

From the figure (5), one can observe that, the number of branches increases with the increasing of the radius channel. That can be explained as the radius channel more elements realized the conditions of the streamer initiation and growth. Also one can observe the decreasing at the arriving time to the plane electrode and it arrives nearest to the center of the plane. In other words, it arrives in shorter distance which means in faster velocity. Increase the number of branches in all cases with the approach of the other pole (plane).

It follows from the above that the number of branches and growth time in water depends on the radius of the flow channel. This is consistent with property formed streamers within the dielectric liquid, which studied many experiential and theoretical researches [29, 30, 31]. Table 1, shows the number of branches and arriving time at each radius channel.

Table 1. The arriving time and the number of branches at each radius channel in water.

radius channel (mm)	Arriving time(µs)	No. of branches
5	3.120	130
10	2.566	147
15	2.501	168
20	2.480	197
25	2.470	213

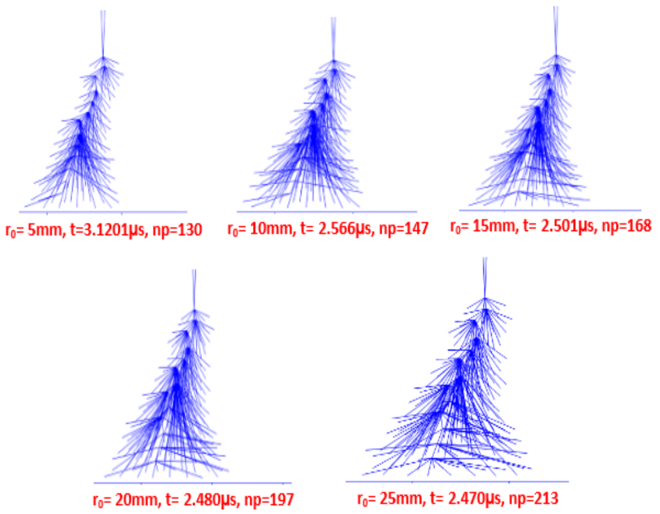


Figure 5. The propagation and branched structures of streamers (At each time step) for different within tip- plane arrangement in water with electrode gap of 2.75 mm when applied voltage17kV.

Characteristics of Streamer

After the growth and development of the streamer within the insulating water was followed the simulation program was implemented to study some of the characteristics of the streamer for each step of the streamer development. Such as streamer velocities, the electrons densities, the degree of ionization, the mobility of charges carriers, and streamer current. Which are explained in some details within the following sections.

The Streamer Velocity

One of the most important parameter which characterizes the streamer is its instantaneous velocity (υ_{se}). And the streamer length was calculated by the difference between the positions of two subsequent steps of the streamer in the solution region.

Figures (6) and Table (2) show the fluctuations of the simulated instantaneous velocity of the streamer steps. One can observe these fluctuations around the average values and increases with increasing the radius of the streamer channel. The fluctuation of the velocity can be explained because the randomly in length of the streamer and the increasing of velocity because of the expected increasing in the ionization with the increasing of voltage.

The average instantaneous velocity values were in good agreement with that indicated in literatures this sort of streamer [32, 33, 34] in the range (4.2 to 21.6 km/s). It should be noted that this average instantaneous velocity was consistent with a strong electric field (E_{tip}), it leads to the development of primary and secondary type of streamers.

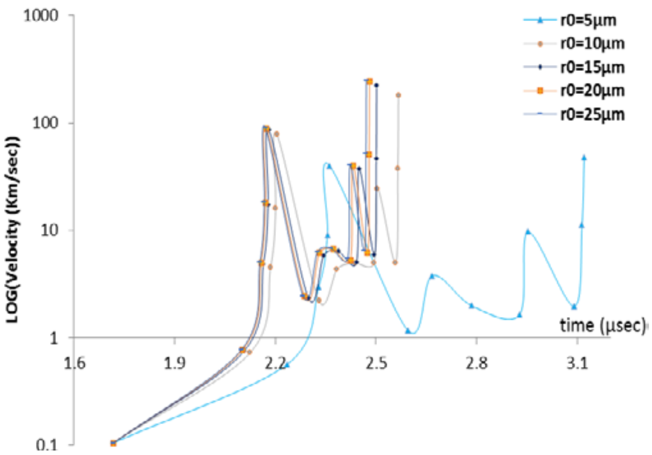


Figure 6. The υ_{se} at every streamer time development step with different the radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

The Electron Density and Degree of Ionization

They are important factor or a main parameter that diagnostics the plasma properties such as Debye shielding, plasma oscillations ...etc,. The streamer was known as weakly ionized plasma channel, so that the calculation of the electron density (n_e) and degree of ionization (D.I) are important to support this idea about the streamer.

Figure (7) shows the density of electrons of different radius of the channel streamer. The electron density values are shown at each step of the runtime by developing gap lengths (2.75 mm).

Figure (7) shows the value of electron density increases according to the flow growth time in all cases with increasing radius of the channel streamer. The density of electrons decreases with the flow time of a single state. These values correspond to the electrons density (plasma density), and are consistent with experimental and theoretical research [35, 36]. Barmanny P. et. al. find the electron densities in the a dielectric liquid between ($1*10^{18}$ and $1*10^{19}$ cm^{-3}) [37]. Sommers B. S. et. al. [38] find the The maximum electron density reaches (4–7)$*10^{15}$ cm^{-3} in the water. Also, Sun A. et. al. [39], they find ionization density of $\sim 10^{24} m^{-3}$. Babaeva N. Y. and Kushner M. J.[40] find the electron densities in the a dielectric liquid between ($4.1*10^{14}$ and $1.4*10^{22}$ cm^{-3}). 41

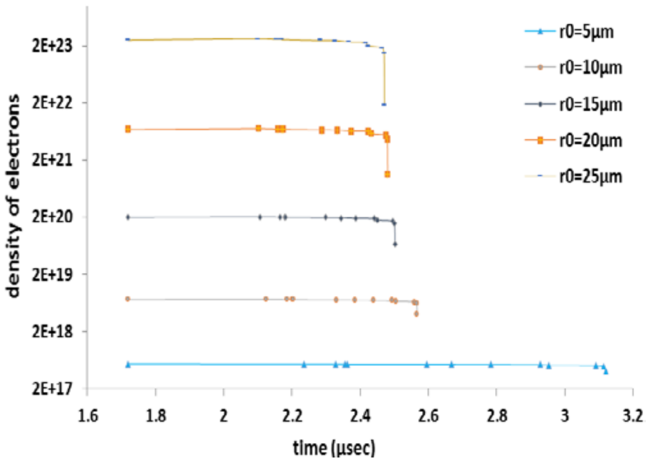


Figure 7. The n_e at every streamer time development step with different radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

Figure (8) The results obtained from the simulation in different radius of the channel streamer of a 2.75 mm gap.

Figures (8) and Table (2) show the degree of ionization (D.I) in all cases increases with time until oncoming voltage drop and decrease the electrons density in every step of the time. These values correspond to the electrons density (plasma density). The degree of ionization decreases with the increase of the growth streamer time at applied voltage, due to drop voltage at each step of the time. Values are shown in the figure the degree of ionization decreases with increasing radius of the channel streamer in all cases. And are consistent with experimental and theoretical research [41]. Where Lin Y. and Adomaitis R. A. find the degree of ionization (10^{-6} to 10^{-1}) [42].

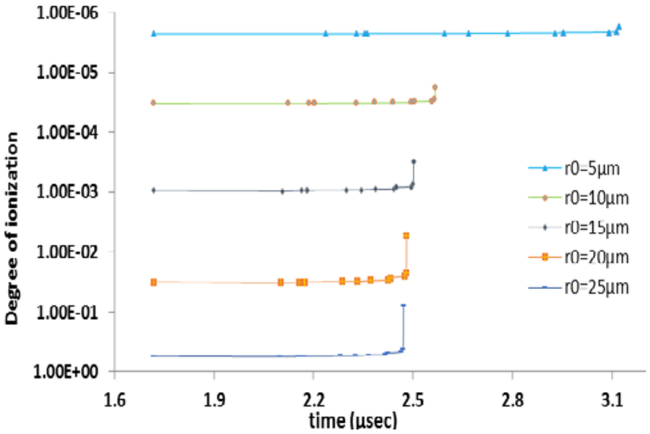


Figure 8. The D.I at each step of the streamer time development with different the radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

The Mobility of charge carriers and The Streamer Current

It is important to know the type of charge carriers ions or electrons to determine the type of carriers in the streamer. The equation was utilized to calculate the charge carriers (μ_c) mobility in the streamer channels for each time step [23, 24, 32, 34].

$$\mu_c = \frac{\upsilon_{se}}{E_{tip}} \quad (3)$$

Figures (9) show the increases of the mobility of charge carriers according to streamer growth time in all cases because of decreasing the electric field (E_{tip}) at the streamer tip in every step of the time. The mobility of charge carriers increases with increasing the growth streamer time at radius of the channel streamer, due to the drop voltage at each step of the time.

Figures (9) show the mobility of charge carrier's (μc) values in all cases increases with increasing the radius of the channel streamer in all cases. This is due to high temperature in the channels of plasma, which causes the increase of collisions between carriers in the channels of plasma. Its values are 100 times higher compared to the model ionic mobility ($10^{-8}m^2.V^{-1}s^{-1}$). The electron is dominant in the streamer growth. These results are in agreement with researches for this sort of streamer [23,34].

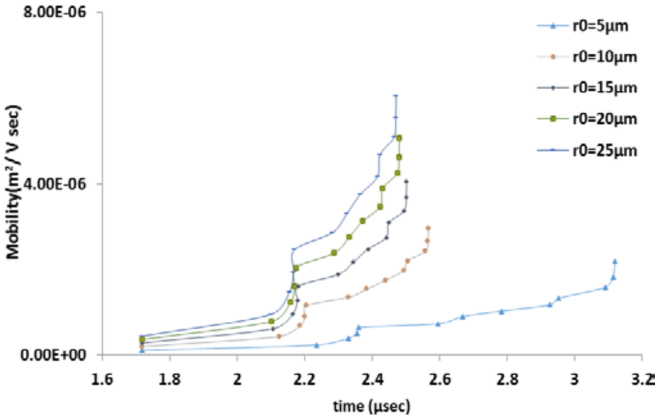


Figure 9. The μ_c at every streamer time development step with different the radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

The streamer current was calculated for each step of the streamer development. The streamer current I to have an initial value I_o and increases linearly with streamer length l_c [43] (in non-dimensional equation) such as;

$$I = I_0 \cdot l_c \quad (4)$$

Figures (10) show fluctuation of the step values of the current around the average value with time development. That is because of their current dependence on the length of the channel which gives the fluctuation of the current at each time step. Table (2) shows the average current increases with increasing radius of the channel streamer in all cases. These results (fluctuation of the current) are in agreement with researches for this sort of streamer [23, 24, 32].

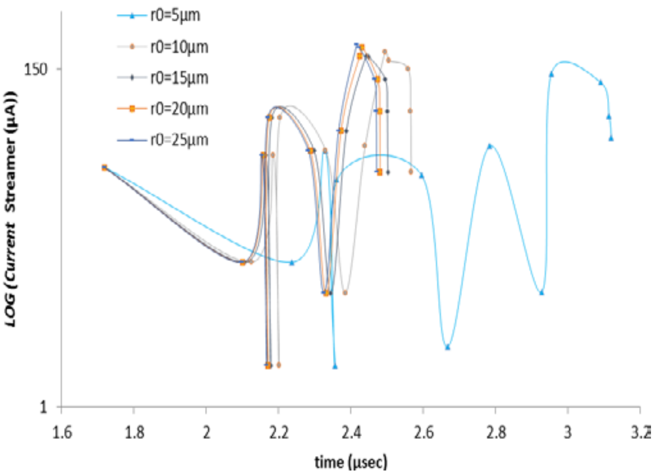


Figure 10. The I at every streamer time development step with different the radius of the channel streamer within pin - plane arrangement in water with electrode gap of D = 2.75 mm.

Conclusions

From the results that are obtained by the simulations which been employed here, the

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following can be concluded:

1. The computational procedure, according to the bubble model, can provide good results in comparison with experimental processes.
2. Increase the number of branches with the approaching to the other pole (plane).
3. The type of streamer is dependent on the electric field at the head. The results show the growth of two types of primary and secondary streamer.
4. The streamer growth with the shortest distance between the electrodes with the increase of the voltages on the anode (pin), which leads to a decrease the streamer time development in all cases.
5. The number of branches and their positions is dependent on the radius of the channel streamer value.
6. The type of streamer depends on the streamer velocity value and the electric field at the head. The results show the growth of two types of primary and secondary streamer.
7. The streamer properties fluctuate around the average values and depend on the radius of the channel streamer and the streamer channel lengths. Also, in general, all average values of streamer properties increase with increasing radius of the channel streamer except the degree of ionization (D.I) decreases with the increase in the radius of the channel streamer.
8. The value of electrons density fluctuates in range satisfies the idea of weakly ionized plasma channels.
9.

Acknowledgments

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