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Townsend Discharge and Streamer Breakdown within Sphere-Air-Sphere Configuration

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Abstract

The main aim of the present paper is to study the electric breakdown in a uniform electric discharge system. The system consists of two spheres separated by a dielectric. The dielectric is dry air. Certain boundary conditions are taken into consideration as applied voltage, pressure, and domain. The formation of discharge types as Townsend and streamer under different distance gaps (1, 0.9,0.8, 0.6, 0.4, 0.2, 0.1) mm was sudied. The temperature effect on the breakdown voltages for the discharge process is also included. Seven different temperature steps are chosen in the study. Comsol Multiphysics software is used for the simulation model as a plasma model. Results show that as the gap distance increases the breakdown voltage increases for each of the discharges. For maximum electric field, as the distance increases the field also increases. For gap distance, the temperature effects are more apparent at the higher values of the pressure. The maximum electric field increases as the voltage increases with the temperature.

Keywords: breakdown voltage, temperature, Townsend, streamer, sphere configuration

تفريغ تاونزند وانهيار التدفق في ترتيب كرة – هواء – كرة

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الخلاصة

الهدف الرئيسي من البحث الحالي هو دراسة انهيار الكهربائي في نظام تغريغ كهربائي منتظم. النظام يتالف من كرتين مفصولتين بعازل. العازل هو الهواء الجاف بين الكرتين. شروط حدودية معينة تم اخذها بالاعتبار مثل الفولتية المطبقة, الضغط, والحيز . تكون انواع التفريغ مثل تاونزند والتدفق تم تحت مسافات فجوة مختلفة (1, 0.9,0.8, 0.6, 0.4, 0.2, 0.1) ملم. تاثير درجة الحرارة على فوليتات الانهيار لعمليات التفريغ كذلك تم حسابه. تم اختيار سبع درجات حرارة في هذه الدراسة. تم استخدام برنامج Comsol Multiphysics لنموذج المحاكاة كنموذج بلازما. تظهر النتائج أنه مع زيادة فجوة المسافة ، يزداد جهد الانهيار لكل من التفريغ. عند اقصى مجال كهربائي ، كلما زادت المسافة ، زاد المجال أيضًا. بالنسبة لمسافة الفجوة ، تكون تأثيرات درجة

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الحرارة أكثر وضوحًا عند القيم الأعلى للضغط. يزداد الحد الأقصى للمجال الكهربائي مع زيادة الجهد مع درجة الحرارة.

1. Introduction

Plasma, the fourth state of matter, can be generated by different devices configurations. The characteristics and diagnostics of plasma are essential steps in each study [1]. One of the necessary characteristics is the electrical breakdown. Electrical breakdown is the focus of scientists. Since it may be used in many electrical systems and electronic devices. In the early 20th century, much research and studies on electrical breakdown were done [2-4]. The point of view from these studies is that this phenomenon is used in different insulating materials, such as thin films [5]. To understand this phenomenon and to employ it in various applications, scientists uses experimental methods and choose different systems and parameters that may affect the behaviour. Others employed simulations of plasma models. To make these studies, one must take into concern the streamer discharge. The importance of streamers or fast ionizing waves to the transient electrical breakdown of gases, streamers are fast-moving ionization fronts that can form complex tree-like structures or other shapes, depending on conditions [6].

In most overvaulted transient discharges at or near atmospheric pressure, an electron avalanche quickly leads to a space charge dominated transport called streamers. Streamers are precursors to arc and lightning formation [7]. The streamers can be characterized into positive and negative streamers due to the starting point. In the discharge gap and when the applied voltage is sufficiently high, the gas molecules in the gap will be ionized by the electrons emitted from the cathode. The electric field accelerates these ionized electrons, and in turn, they will ionize other gas molecules [8]. Townsend breakdown and streamer breakdown voltages are also taken into concern. Many studies were done for different discharge configuration systems, such as cylinder electrodes [9], spheres [10], and different insulating gases and gap distances [11-16] and electrical conditions [17].

In this work, numerical simulation model was used to provide a better physical understanding of the two discharges. The effect of the environmental parameters, such as pressure and temperature, in addition to the separation distance, on the breakdown voltage and the corresponding maximum electric field in air between two spherical electrodes were studied.

2. Modeling of the problem

In the present work, a plasma model was used to study the electrical breakdown between two spheres separated by a certain distance. Dry air is considered the insulating medium for this method. For achieving a self-sustaining discharge, the breakdown requires a specific condition that is [12,13]:

$$\gamma i \left(\exp \int_0^D N\alpha ds\right) - 1) = 1 \qquad \text{........ (1)}$$

Where: N is the ion number density, γ_i is the secondary emission coefficient, α is the reduced Townsend growth/decay coefficient, D is the distance between the source boundary and any destination boundary, and s is the arc length along the particle trajectory. The model illustrates three states for the solution; one is when the discharge is not taking place yet, by satisfying the following condition [13]:

$$\int_0^D N\alpha ds < \ln\left(1 + \frac{1}{\gamma i}\right) \qquad \text{... ... ... (2)}$$

The second state is at a sustained discharge, which happens when the solution of Equation 1 is greater than 1. The breakdown can be localized or pass over the gap distance. For the first one, it will limit in current carrying capability. For the second, it will have the ability of large current conductions. The third state is when the Townsend condition is gathered [13]:

$$\int_0^D N\alpha ds > \ln\left(1+\frac{1}{\gamma i}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

When the left hand side exponential is greater than approximately 10^8, a streamer is created throughout the gap. So, the streamer condition in mathematical form is [13]:

$$\int_0^D N\alpha ds \; > 17.7 + \ln(d/(1[cm])) \quad \ldots\ldots\ldots (4)$$

Where: d is the gap distance in cm and α is the reduced Townsend coefficient. The physics interface of the detection of the electrical breakdown is assigned a variable. This variable has three values due to discharge. Its values are 0 for no discharge take place yet, equals to 1 when there is a sustained discharge, and equals to 2 when the streamer state begins. The reduced Townsend coefficient is related strongly with the reduced electric field by the relation $\alpha = \alpha\left(\frac{E}{N}\right)$ where E is the electric field parallel to the streamlines. Solving Poisson's equation determines this electric field. The integral is computed by solving an ordinary differential equation along the test particle trajectories:

$$\frac{d\alpha_D}{ds} = \alpha\left(\frac{N}{N_{step}}\right) \ldots \quad \ldots\ldots\ldots\ldots\ldots. \quad (5)$$

Where: N_{stp} is the number density at standard temperature and pressure.
In this model, the Townsend growth coefficient is taken using the dry air option, which uses an interpolation function for the growth coefficient versus the reduced electric field.
The domain of the model is a 3D cube system with (20×20×20) cm dimensions. Two spheres are used as a discharge system. The sphere radius is 2 cm, with different gap distances between the two spheres. Figure 1 is the domain of the solution chosen in the research.

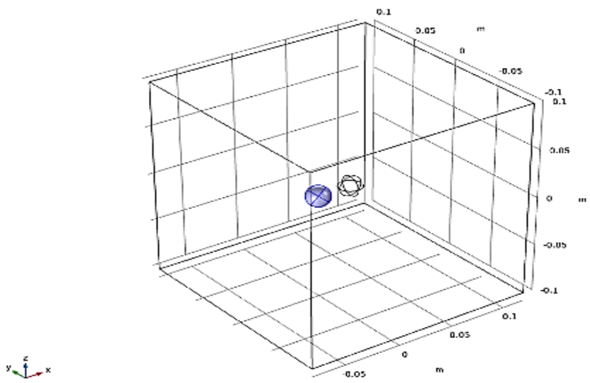


Figure 1: Domain of the solution region in 3D.

The Finite Element Technique (FET) was used to solve the model numerically so that the domain of the solution region is discretized to a sub small regions or elements as a mesh. In 3D models domain mesh, there are four different element types: tetrahedral, bricks, prisms, and pyramids. The most popular used element in physics models is the tetrahedral element type. This is due to its simplicity and the fact that it can be used at any volume in 3D despite shape or topology. Another reason of using these elements in a mesh is that they can be used with adaptive mesh refinement. The test mesh has about 145,000 elements and around 730,000 degrees of freedom. Figure 2 shows the mesh of the domain.

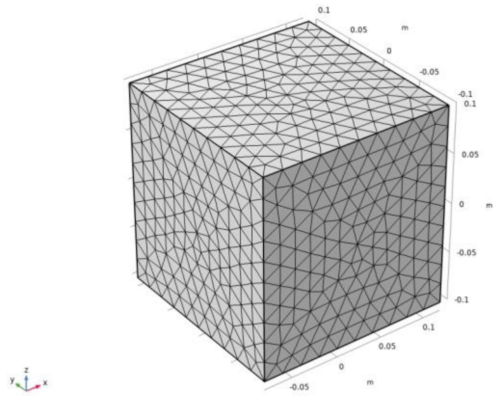


Figure 2: Meshing of the solution domain in 3D.

3. Results and discussions:

Electrical breakdown characteristics between two spheres separated by dielectric material as dry air was modelled. Solving plasma model equations that are part of Comsol Multiphysics package version 5.6 was used to simulate the problem. The results were obtained under the action of applied negative high voltage. The Townsend discharge and streamer breakdown voltages and the corresponding electric fields at different pressure, temperature and separation distance were investigated.

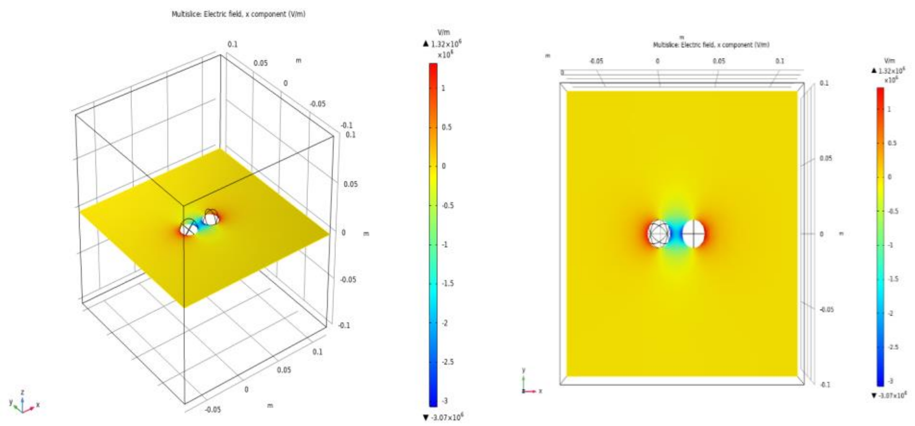
3.1 Indication of Townsend discharge and Streamer breakdown.

A test simulation was executed at atmospheric pressure (*1 atm*), room temperature ($20\,\dot{C} \equiv 273.15\,K$) and 1cm distance between the spheres electrodes to detail the procedure of the indication of Townsend discharge and streamer breakdown voltages. The applied voltage was increased negatively until the Townsend condition, Equation (3), was satisfied at *-22.6 kV*.

Figure 3a represents the surface distribution for the x-component of the electric field for a layer at the shortest distance between the sphere (the interest region) in the 3D domain. For more clearness, the x-y plane is shown in Figure 3b. The maximum negative value of the electric field was $-1.07\times10^{6}\ V/m$ which was indicated as dark blue near the shear.

For streamer breakdown, the same distribution was found, but the maximum electric field value was $-4.18 \times 10^{6}\ V/m$ at a voltage of *-30.8 kV*, which satisfies the condition of Equation (4).

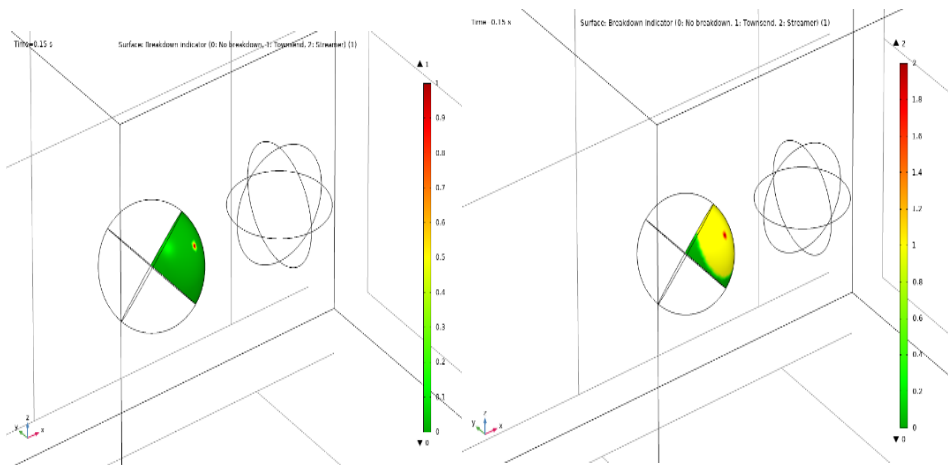
The indication of the voltages was presented as surface distribution on the cathode sphere. When the voltage value doesn't satisfy the conditions of the discharge and breakdown, the indicator is zero, while Townsend discharge was one and two for streamer breakdown.



(a) (b)

Figure 3: Surface distribution for the x-component of the electric field, a) a layer at the shortest distance between the spheres, b) x-y plane.

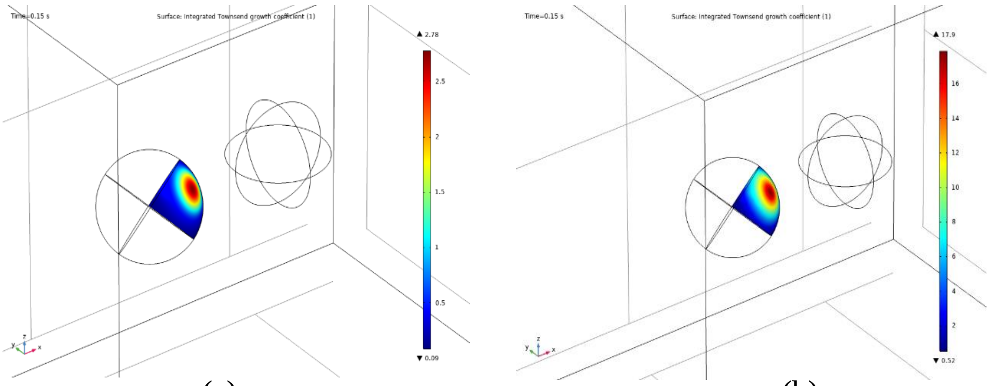
For this test, as shown in Figure 4a, the indicator is 1 which is shown as small red spot on the surface, while in Figure 4b, the indicator is 2 as shown as small red spot on the surface, that occurs at -22.6 kV for Townsend and -30.8 kV for the streamer.



(a) (b)

Figure 4: Surface indication of electric discharge as: a) Townsend discharge, b) Streamer.

Another criterion for the indication is the Townsend coefficient, it has a value of approximately 18 for streamer breakdown and less for Townsend discharge. Figure 5 presents Townsend coefficient growth for Townsend discharge (a) and streamer breakdown (b)**.** From the Figure and at time 0.15 sec, the secondary ionization occurred rapidly and with higher Townsend coefficient growth value in streamer than in Townsend discharge. The growth coefficient is about six times of Townsend discharge less than the streamer breakdown.



(a) (b)

Figure 5: Surface indication of Townsend coefficient growth for: a) Townsend discharge, b) Streamer breakdown.

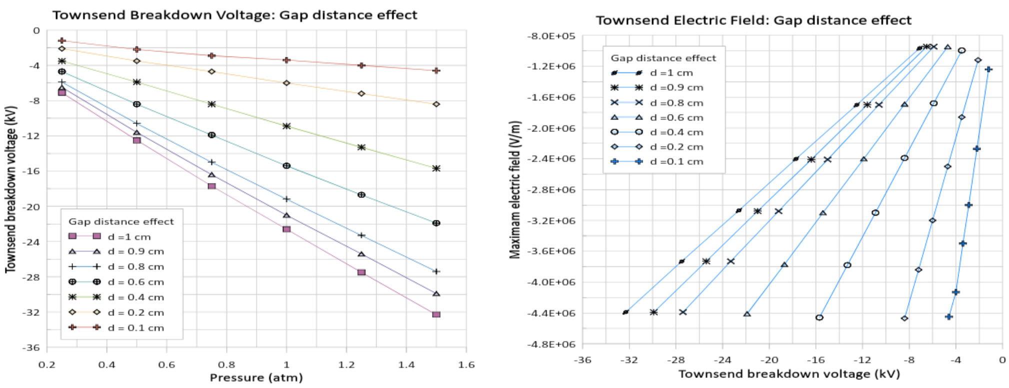
3.2 Townsend Discharge

To indicate the Townsend discharge voltage and the corresponding maximum electric field, the simulation was executed as in the procedure above. The simulation was done at pressure range around the atmospheric value (from 0.25 atm to 1.5 atm) and temperature range around room temperature value (from -40 ^{o}C to 80 ^{o}C) and with different gap distances from 0.1 to 1 cm. For each case, the applied voltage was gradually increased (negatively) until the Townsend discharge conditions were satisfied. Then the voltage and the corresponding maximum electric field were recorded.

3.2.1 Gap distance effect

One of the most important parameters in the electric discharge systems is the gap distance between the electrodes. Figure 6 shows the gap distance effect on Townsend discharge voltage. Figure 6(a) shows the breakdown voltage as a function of pressure. It is noted that as the pressure increased the discharge voltage increased (negatively) for each gap distance. Also, as expected, the breakdown voltage increased (negatively) as the gap distance increased.

The most important note is that the differences for different distances increase with the increase of pressure, which can be explained because the loss of energy increases with the increase of the elastic collisions. Figure 6(b) presents the maximum electric field as a function of breakdown voltage. From the figure, it can be noted that as the breakdown voltage increases, the field also increases, and as the distance of the gap increases, the breakdown voltage decreases.

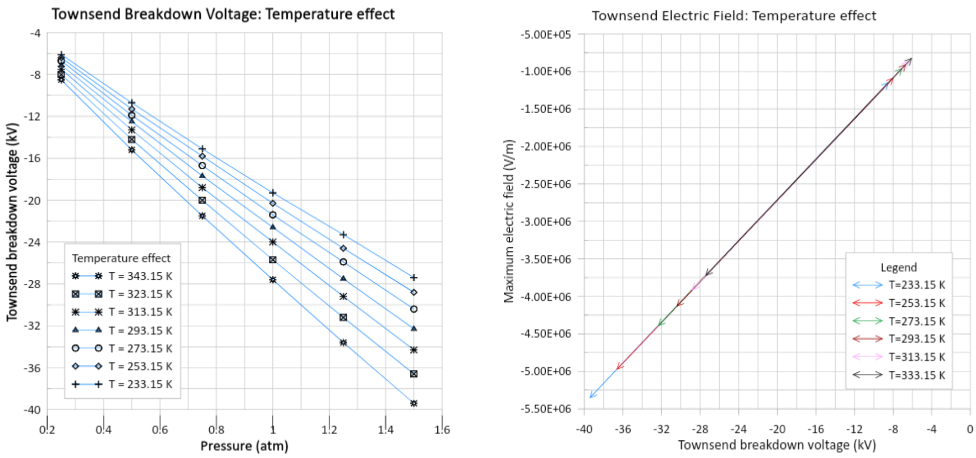


(a) (b)

Figure 6: Gap distance effect on Townsend breakdown a) breakdown voltage as a function of pressure, b) maximum electric field as a function of breakdown voltage.

3.2.2 Temperature effect

Figure 7 presents the effect of temperature on Townsend discharge voltage (a) breakdown voltage, and (b) the maximum electric field near the cathode sphere corresponding to the discharge voltages. From the figure, as the temperature increases, the breakdown voltage increases. This is due to the fact that electron emission from the cathode surface is suppressed. As in the case of gap distance, the temperature effects are more evident at the higher values of the pressure. Also, the maximum electric field increases as the voltage increase with the temperature.



(a) (b)

Figure 7: Temperature on Townsend discharge a) breakdown voltage, b) maximum electric field.

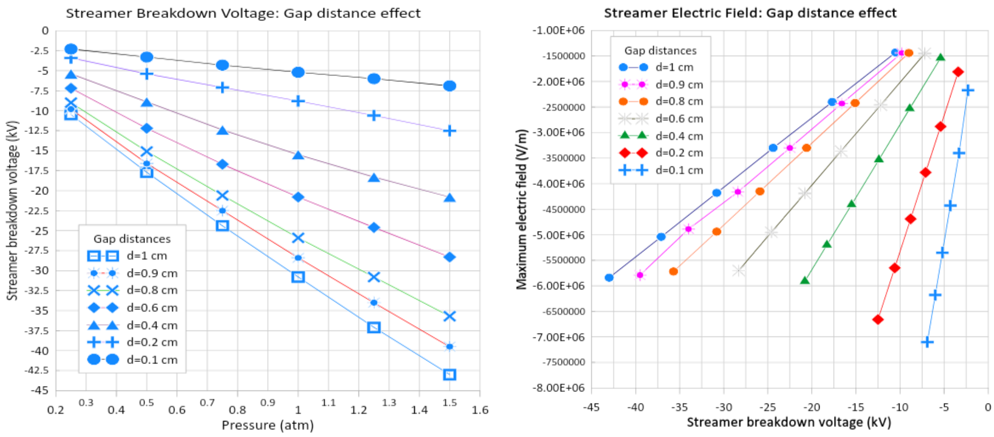
3.3 Streamer Breakdown

The simulation was repeated with the same conditions as in section 4.2 and in the same procedure to indicate the streamer breakdown voltage and the corresponding electric field. The recorded voltage and electric field values were greater that for Townsend discharge.

3.3.1 Gap distance effect

Figure 8 shows the gap distance effect on streamer breakdown for (a) breakdown voltage as a function of pressure and (b) for maximum electric field as a function of breakdown voltage.

From the figure, it is clear that as the pressure increases, the breakdown voltage increases (negatively) for all gap distances, which can be explained as in the left of the Paschen curve. As expected, when the gap distance increased, the breakdown voltage also increased. Maximum values of the electric field follow the same behaviour as the breakdown voltage. Also, in the streamer cases, the same behavior was noted for Townsend discharge but at greater values.

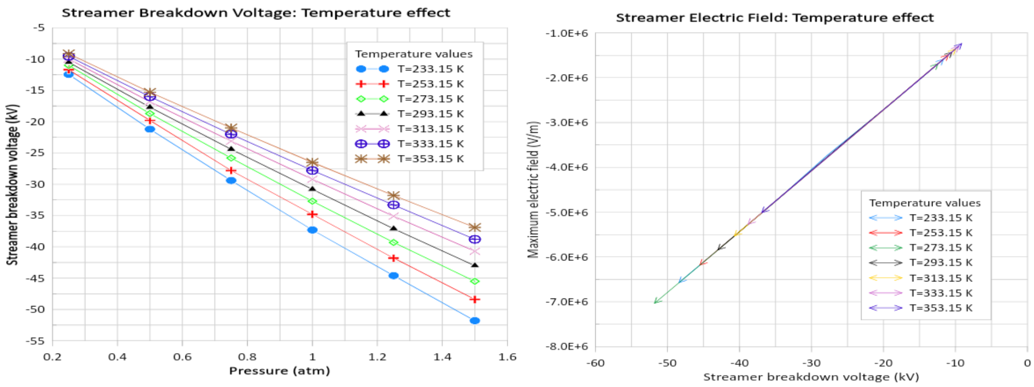


(a) (b)

Figure 8: Gap distance effect on streamer breakdown a) breakdown voltage as a function of pressure, b) maximum electric field as a function of breakdown voltage.

3.3.2 Temperature effect

The temperature effect on the streamer breakdown voltage and the corresponding electric field are presented in Figure (9). It can be noted that the breakdown voltage increased, when the temperature increased and that it is more evident at the higher pressure values. Also as the cases of the Townsend, the electric field show the same behavior but at higher values.



(a) (b)

Figure 9: Temperature effect on Streamer breakdown a) breakdown voltage as a function to pressure, b) maximum electric field as a function to breakdown voltage.

4. Conclusions

From the above results, one can conclude that:

- Townsend discharge and streamer breakdown have the same behavior at different gap distances and the environment parameters pressure and temperature.
- Streamer discharge at all the studied conditions occurs at higher voltage values.
- The effect of the gap distance and temperature is more evident at higher values of pressure.

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