

Dependence of inter-electrode gap separation on the Positive and Negative Point-Grid Plasma Corona Discharge

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ABSTRACT

In this work, both positive and negative corona discharge of point-grid geometrical configuration was studied, and the necessary modification of the general law of corona discharge was proposed. The current-voltage measurements were performed at 300 K and different inter electrode separations. The variation of dimensional constant K and corona inception voltage V_0 with point-grid separations S were subjected into the general law of corona discharge using the least square fitting method on $\log_{10}$ scale. The relationship between corona current and different voltage ($V-V_0$) was used to find the acceptable value of exponent n. The least square fitting for all variations of corona parameters was based on the highest R-square value of the straight lines obtained for individual measurements. It was found that value of exponent n for both polarities is larger compared to the empirical formula proposed previously for the general law of corona discharge.

KEY WORDS: Corona Discharge, Corona inception Voltage, Point-grid electrode system.

1. INTRODUCTION

Corona discharge generally refers to the electrical discharge phenomena in the vicinity of conductors of small radius of curvature such as sharp points and thin wires [1]. This type of plasma discharge is characterized by relatively highest voltage values and lowest current values ranging from 10^{-7} – 10^{-5} amperes compared to all other electric discharge scenarios. These phenomena have been called coronas because of some similarity between them and the glow or corona surrounding the sun which is seen during a total eclipse of the sun. Corona discharge occurs only if the field is sharply nonuniform. The field near one or both electrodes must be much stronger than in the rest of the gap. It is always a time dependent phenomenon even when a dc voltage is applied between the electrodes [2]. Corona discharge has been studied for many years because of its potential applications. The corona discharge in point-plane electrode geometry has been used as a negative ion source in electrical appliances, and in mass and ion mobility spectrometers [3]. Coronas may be positive or

negative. This is determined by the polarity of the voltage on the highly curved electrode. If the curved electrode is positive with respect to the flat electrode, one has a positive corona, but if it is negative, one then has a negative corona. The physics of positive and negative coronas is strikingly different. An important reason for considering coronas is the production of ozone around conductors undergoing corona processes. A negative corona generates much more ozone than a corresponding positive corona [4]. The current that usually carried out by corona discharge flows from a high potential electrode and ionizes the working neutral fluid to create plasma around the electrode. This happens, when the geometrical configuration of the electrodes includes an electrode of sharp tip such as point-to-plane, point-to-grid, sphere-to-plane and wire cylinder electrodes. If the potential of the sharp (tip) electrode is large enough, the fluid at tip point ionizes and becomes conductive leading to the formation of highly curved region on electrodes [5]. Several empirical formulas have been proposed to describe the current-

voltage characteristics of corona discharges, although the physical mechanism of corona discharge is not yet clear. Townsend in 1914 first derived a formula to characterize the dc steady corona current- voltage relationship for coaxial cylindrical geometry. Later it was empirically found that the Townsend relation could also be used approximately for point-to- plane geometry, as Henson disclosed [4]. This formula is given as:

$$I = AV(V - V_0) \quad (1)$$

Where I is the corona discharge current, V the supplied voltage, V_0 the corona inception voltage and A is a constant depending on the inter electrode distance, the needle electrode radius, the charge carrier mobility in the drift region and other geometrical factors. Another kind of empirical relation referred to by Ferreira [5] is as follow:

$$I = K(V - V_0)^2 \quad (2)$$

where K is a dimensional constant which is determined experimentally. In essence of the equation (1) and equation (2), By comparing the linear dependence of I/V versus V and $I^{1/2}$ versus V , Ferreira et al [5] found that for negative corona discharges equation (2) performs better in all the inter-electrode ranges than equation (1). Equation (2) may hold only when the inter- electrode distance is greater than 15 mm. All these indicate the existence of some inconsistencies in the applications of the formula mentioned and that there were still no determinate answers.

An experimental investigation of the current - voltage characteristics for positive and negative corona has been demonstrated by Xiangbo [6] as:

$$I = C_1 S^{-0.41} (V - C_2 S^{0.51})^{1.6} \quad (3)$$

where C_1 and C_2 are coefficients which depend on electrode geometry and ambient conditions. This empirical formula met with some physical difficulties in explaining the results.

2. EXPERIMENTAL SETUP

The experimental setup is shown in figure 1. In order to produce the corona discharge from a system of point-grid electrodes, a glass chamber is used. Both working pressure and temperature are fixed. A high voltage power supply was used, and the applied voltage gradually increased by rate of 100 volts respectively. Simultaneously, the value of the corona current as the function of the applied voltage was recorded by a current micrometer.

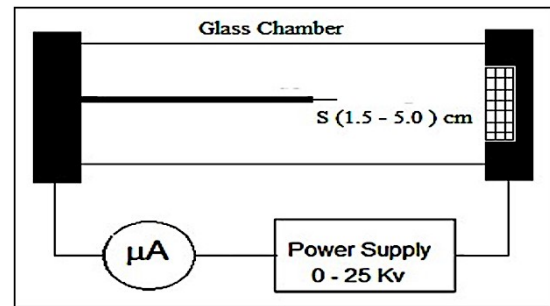


Fig. 1. Experimental setup of pin-grid electrodes configuration

The apparatus of the experimental system consisted of a needle (0.25 mm in diameter) and a thick disk with a center hole (diameter 10 mm) covered by a stainless-steel wire grid (mesh 3x3 mm²; 1.5 mm in diameter). A positive and negative high-voltage dc power supply connected to the needle through a microammeter where the corona current flowing through the inter-electrode gap separation was recorded. The inter-electrode gap separation S between pin-grid electrodes was varied from 1.5 to 5 cm. The corona currents I were measured as a function of discharge voltage V while varying the gap separation S . The experimental work of the present study was carried out at atmosphere pressure, room temperature (300 K) and humidity (45 - 65%) in the preglow regime.

The empirical formula proposed by Ferreira [5] was used to declare the validity of the considered geometry configuration of the point-grid electrodes. All the values of the inception voltages V_0 were recorded experimentally for positive and negative corona

discharge at different inter-electrode separations S . At constant temperature T , the dimensional constant K values referred to by Ferreira [5] formula were obtained from the current-voltage characteristics using least square fitting method for different inter-electrode separations. Finally, the general law of corona discharge has been modified depending on the current-voltage characteristics of the considered point-grid electrode system.

3. RESULT AND DISCUSSION

The experimental data of current – voltage characteristics were carried out for positive and negative corona discharge at different gap separations between point-grid electrodes. A non-linear behavior of corona discharge was found between current – voltage data as shown in figure 2. The corona current for both polarities follow a straight dependence versus applied voltage in the low energy region where different sources of ion is providing in the chamber gap between the point and grid.

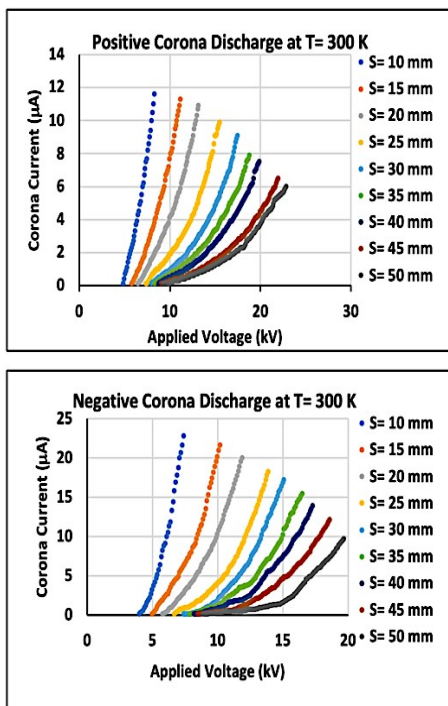


Fig 2. Current-voltage characteristics of point-grid corona discharge for both polarities at 300 K and different inter electrodes separations S .

The corona current decreases as the separation S between the electrodes increases. This correlation is due to the low rate of ionization around the stressed point electrode and low charge mobility in the drift region. The corona current for voltage in negative corona discharge is higher than the corona current in positive corona discharge and this can be attributed to the mobility of the negative ions. When the discharge has a positive resistance at a fixed temperature, the corona inception voltage V_0 decreases more for negative corona than that for positive corona as S increased. In addition, the corona current generated by the discharge is reduced when the inter-electrode gap separation S increases [3, 5].

All the acquired data of current and voltage shown by figure 2 for positive and negative corona discharge were subjected to the empirical formula proposed by Ferreira [5] as referred to by equation (2). This formula was applied by testing $I_{1/2}$ against applied voltage V as shown in figure 3. An increase in the electronic component of the total discharge of the corona current explained the upward trend of $I_{1/2}$ versus the applied voltage V [6]. The method of least fitting square was used to verify the cross matching between the Ferreira formula and the experimental (I-V) data of the present work. The investigation shows a good agreement in the high energy region. However, it can be mentioned that not all data were in perfect agreement with Ferreira formula in the low energy region. The corona current follows a linear behavior with applied voltage as $I_{1/2}$ plotted against V as indicated by figure 3. Using the least fitting square method, a straight line was generated individually for all (I-V) data at different point-grid inter electrode separations S . This verified the relationship between the experimental (I-V) data with Ferreira empirical formula for all inter electrode separations and ensured the validity of using the geometrical configuration of the present work in the general formula of Townsend corona discharge.

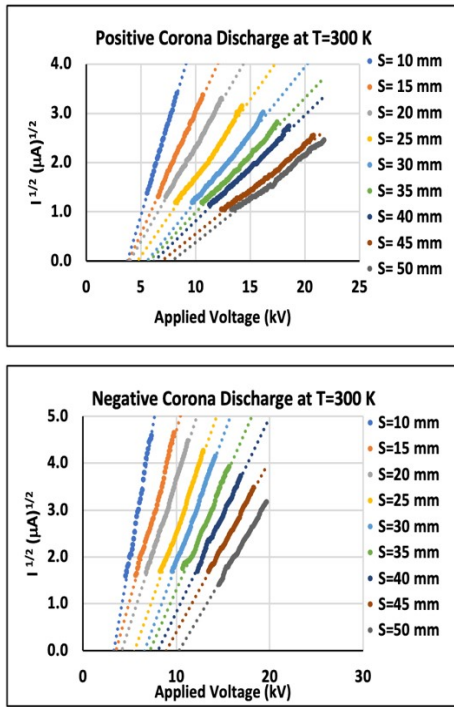


Fig. 3. Testing $I^{1/2}$ against applied voltage V for both polarities of point-grid geometry with different inter electrode separations S at 300 K.

The variation of dimensional constant K referred to by Ferriera formula with point-grid inter electrode separation S for positive and negative corona discharge is illustrated in figure 4.

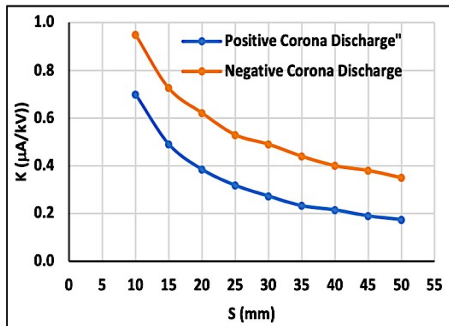


Fig 4. The variation of dimensional constant K against inter electrode separations S for positive and negative corona discharge at 300 K.

All values of K were extracted from the testing of $I^{1/2}$ versus the applied voltage V shown in figure 3. The value of dimensional constant K depends on some geometrical factors (point-grid separation, pin radius and grid dimensions) and on the mobility and the permittivity in vacuum [9]. The relationship between K and S shows a nonlinear behavior. This can be explained by some

experimental conditions and the influence of point-grid separation S on the current-voltage characteristics for both polarities of corona discharge. Furthermore, a higher value of dimensional constant K for positive corona discharge was obtained compared to the negative corona discharge at same point-grid separations S . At small inter-electrode gap separation between point and grid electrodes, the highest values of K are determined. This contributed to the high charge carrier mobility in the drift region. Figure 4 represents the nonlinear proportional of K with S as:

$$K \propto S^x \rightarrow K = a S^x \quad (4)$$

The linear dependence between K and S can be expressed by taking the Log_{10} for both K and S in the above equation as:

$$\text{Log}_{10} K = x \log_{10} S + C_1 \quad (5)$$

Where $C_1=10^a$. the Log_{10} scale for the variation of K with S at 300 K for both polarities of corona discharge are plotted in figure 5. The solid line generated by least square fitting resulted from an inverse proportional between K and S with R-square value of 0.9994 and 0.9996 for positive and negative corona discharges respectively. The values of proportional exponent x were found (-0.8626) for positive corona ($K \propto S^{-0.8626}$) and (0.6114) for negative corona ($K \propto S^{0.6114}$). The values of constant C_1 were found to be (0.3576) and (0.059) for positive and negative corona discharges respectively.

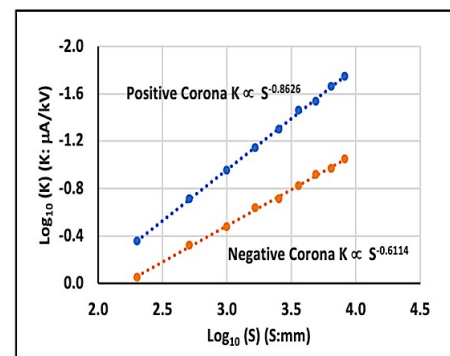


Fig. 5. The variation of K versus S for positive and negative corona discharge at 300 K on Log_{10} scale. The solid line is obtained by least square fitting.

The corona inception voltage V_0 represents the starting point at which the breakdown discharge reaches the threshold condition of corona discharge. The variation of corona inception voltage V_0 with point-grid inter electrode separations S for positive and negative corona discharge is shown in figure 6. The corona inception voltage is basically depending on some geometrical configuration of the electrodes used such as the sharp point of pin electrode and inter electrode separations. The determination of an accurate corona inception voltage depends on abrupt negative corona voltage and it is essentially independent of the corona current and applied voltage [3]. Many experimental and theoretical studies were attempted to predict the value of corona inception voltage [10, 11, 12]. It was found that the voltage corresponding to the initial current at which the corona is stable can be considered as the estimated value of V_0 and falls on the range (0.1-1 μ A). This range was clear enough in the present work and it has been depended for determining the potential scope of corona inception voltage.

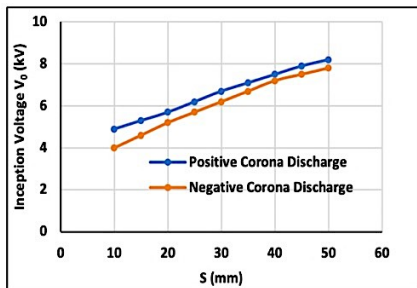


Fig. 6. The variation of corona inception voltage V_0 against point-grid electrode separation S for positive and negative corona discharge at 300 K.

Figure 6 shows a nonlinear dependence of corona inception voltage against point-grid electrode separations S for both polarities of corona discharge. As S increases, much more applied potential is required to reach the starting point of threshold condition for corona inception voltage. It was found that the values of V_0 for positive corona discharge is higher than the negative corona discharge. This can be attributed to the fine and small cross section area of sharp point of pin electrode

which needs a less potential to reach the breakdown discharge of negative corona compared to the positive corona. This fact has also been observed for other configurations at different inlet gases [13]. A nonlinear behavior of V_0 with S is observed as shown in figure 6 gives:

$$V_0 \propto S^y \rightarrow V_0 = b S^y \quad (6)$$

Similarly, the linear dependence between V_0 and S can be expressed by taking the $\log_{10}$ for both V_0 and S in the above equation as:

$$\log_{10} V_0 = y \log_{10} S + C_2 \quad (7)$$

where the constant $C_2 = 10^b$. The corresponding correlation between the corona inception voltage and point-grid electrode separations for both polarities of corona discharge as shown in figure 7, shows the corresponding linear dependence between V_0 and S where $\log_{10}(V_0)$ is plotted versus $\log_{10}(S)$. The solid lines were obtained through the least square fitting method for all values of corona inception voltage V_0 with respect to their point-grid electrode separations S . A high R-square values of 0.9974 and 0.9995 were found for positive and negative corona discharge respectively.

The optimal value of proportional exponent y was found to be 0.3342 and 0.428 for positive ($V_0 \propto S^{0.3342}$) and negative ($V_0 \propto S^{0.428}$) corona discharge respectively. Whereas the value of the dimensional constant C_2 takes 1.5452 and 1.3641 for positive and negative corona respectively.

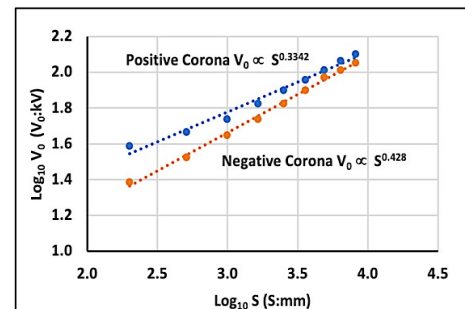


Fig. 7. The variation of V_0 with S for positive and negative corona discharge at 300 K on $\log_{10}$ scale. The solid line is obtained by least square fitting.

According to the experimental results of the present work, it becomes possible to explore the relationship between the corona discharge current I and Voltage difference $(V-V_0)$ according to the essential assumption referred to by Xaingbo [6]:

$$I = K (V - V_0)^n \quad (8)$$

This equation can be given on Log_{10} scale as:

$$\text{Log}_{10} I = n \text{Log}_{10}(V - V_0) + C_3 \quad (9)$$

The experimental data of corona current I and different voltage $(V-V_0)$ followed a linear dependence on Log_{10} scale through least square fitting method for positive and negative corona discharge as shown in figure 8. Accordingly, an acceptable value of the exponent n can be obtained from equation (9) using all data of corona current, corona inception voltage V_0 and applied voltage. The method of least square fitting is usually used to find the best R-square value of straight lines for each point-grid electrode separation individually. The slope of such straight lines gives the estimated values of the exponent n .

The value of exponent n is basically independent on the inter electrode separations for both positive and negative corona discharge, but it influences by the case sensitivity of extracting the values of corona inception voltage [14]. More accurate corona inception voltages at different point - grid electrode separations are considered the minimum values of observed corona inception currents between $(0.1 - 1 \mu\text{A})$ for both polarities of the present study. As shown from figure 8, the estimated values of exponent n tend to decrease as the corona inception voltage increases, which in turn reduces the curvature of the current-voltage characteristics of positive and negative corona discharge.

The curvature of corona discharge was shifted upward more in negative corona compared to the positive corona. The geometrical configuration of point-grid electrodes showed that the optimal value of exponent n takes $3.5 \pm$

0.05 and 4.5 ± 0.4 at all pin-grid electrode separations for positive and negative corona discharge respectively. The optimal value of n presents the best linear dependence of corona current versus the difference voltage $(V-V_0)$.

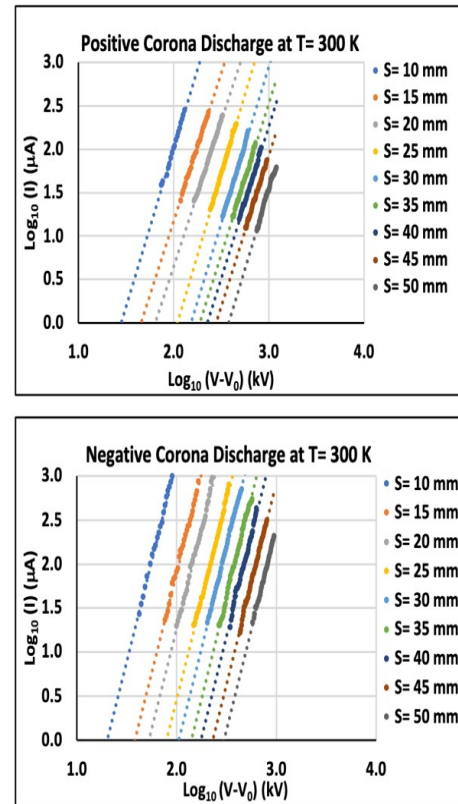


Fig. 8. Corona current versus different voltage $(V-V_0)$ on Log_{10} scale for positive corona and negative corona discharge for different point-grid electrode separations at 300 K.

It was found that the value of exponent n for both polarity in the present work is quite larger compared to the empirical formula proposed by Ferreira [5]. This satisfied that the value of the optimal value of exponent n depend essentially of some configuration parameters regarding the electrode geometry. In addition, the value of exponent n is influenced by the corona inception voltage V_0 . However, several experimental works were performed at various ambient conditions and different geometrical configurations to show the dependence of optimal value of exponent n to other controllable parameters such as the type of the gas, relative humidity (RH), gas pressure (P), temperature (T) and different geometrical configurations [15].

The proposed empirical formula for the point-grid electrode configuration at 300 K and different interelectrode separations can be disclosed from the experimental results of the dimensional constant K, corona inception voltage V_0 and the inter- electrode gap separations S considered in the present study. The general law of corona discharge assumed by Xaingbo [6] as referred to by equation (3) can be described as:

$$I = C_1 S^x (V - C_2 S^y)^n \quad (10)$$

where C_1 and C_2 are coefficients depend on the geometrical configuration of the electrodes. Table 1 collects all the determined parameters from the present work regarding the dimensional constant K and corona inception voltage V_0 with their proportional dependence on the point-grid electrode separations S.

Table 1. The values of the corona parameters determined from the proportional dependence of the constants K, V_0 and S for positive and negative point-grid electrode system at 300 K.

Constants	C_1	x	C_2	y	n
Positive Corona	0.3576	-0.8626	1.545	0.3342	3.5 ± 0.05
Negative Corona	0.059	-0.6114	1.364	0.428	4.5 ± 0.04

4. CONCLUSIONS

The corona current for both polarities follow a straight correlation with applied voltage in the low energy region and decrease as the separation S between the electrodes increases. The corona inception voltage V_0 decreases more for negative corona than that for positive corona as S increased. The relationship between K and S shows a nonlinear behavior for both polarities. A nonlinear dependence of corona inception voltage V_0 on the inter-electrode separations S was observed for both polarities. It was found that the value of exponent n for both polarities is quite larger compared to the empirical formula proposed previously. Accordingly, the corona discharge of point-grid electrodes was found to be obeyed to Townsend relationship. Whereas, the

experimental results disclosed that the configuration of point-grid electrodes met with some difficulties in matching with empirical formula proposed by Ferreira.

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