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Experimental observation of negative differential characteristic of corona discharge in ultraviolet spectrum

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ABSTRACT

Corona discharge is a self-sustained discharge which appears at electrodes with a small radius curvature in gas insulation. An almost invisible glow occurs just above the inception voltage. Corona phenomenon is mainly used in electro-technological processes to obtain space charge for electrostatic precipitation, separation of different particles, electrostatic liquid or solid coating, neutralization of space charge, etc. All of these processes rely on a strong nonhomogeneous electric field generated by a point – plate electrode system. When the critical value of the applied voltage is reached, the ionization processes near the point electrode start and give rise to the current between two electrodes. If the pointed electrode is positive, it is possible to observe an anomaly of the current – voltage (I-U) characteristic for the point-plate space. It means that while the voltage is raising the current density decreases in a narrow voltage area (2–3 kV). The anomaly was technically named as negative differential conductivity ($dI/dU < 0$). Unstable current can have a negative influence on electro-technological processes. The anomaly was detected for different shapes and materials of the electrode as well as for various temperatures and distances between electrodes. An oxidation layer, which appears on the metal electrode, also influences the ionization processes near the pointed electrode and causes a decrease of a current. In this paper measuring of the discharge activity in a point – plate electrode system is presented. Ionization of gas atoms and molecules in a high electric field and the following recombination of electrons and positive ions in the corona region can give rise to high-energy photons which produce new electrons in the field of discharge. Corona discharges are detected by DayCor Corona camera which can register UV emission generated by corona in a day light. The experiment was conducted with various shapes of the pointed electrode and distances between the high voltage and the grounded electrode under applied direct voltage with positive and negative polarity.

1. Introduction

This paper studies a space charge which is generated in the space between a point and a plate electrodes when a high voltage is present at the point electrode. The space charge generated in a strongly nonhomogeneous electric field finds wide usage in electrical engineering, such as electrostatic precipitation, separators for particles with various permittivity, neutralizers of electric charge, during liquid coating, dust plastic application, etc. Various methods could be used to study processes taking place in the space between electrodes, for example electrical, acoustic, optical and others.

The space charge plays a main role in the usage of corona discharge in electrostatics. The space charge is generated when a critical intensity of electric field is reached near the electrode with a small radius of curvature. When a DC voltage is present at the electrode, a positive or negative space charge appears depending on voltage polarity. The positive space charge is generated by positive ions, the negative charge is generated by electrons and negative ions. As electrons have much higher mobility than ions, the behavior of space charge between electrodes is different for the positive and negative voltage polarity. For the same electrode layout and the same distance between two electrodes, a different value of critical voltage of corona initiation can be measured. Additionally, the value of the breakdown voltage differs depending on the polarity of the applied DC voltage. This effect is known as a polarity effect. The polarity effect causes that for the same electrode layout and the same applied voltage, a different value of the corona current can be measured for the positive and the negative polarity

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of the DC voltage.

The amount of space charge can be measured by measuring the current flowing from the corona electrode to the opposite electrode. The effectivity of corona electrodes can be evaluated using the current-voltage characteristics. Using this characteristic, the power consumption of maintaining the corona discharge can be calculated or it can be used as a parameter for process regulation in devices using the corona discharge. In some cases of electrode layouts (e.g. coaxial cylinders, wire against plate and others) a mathematical model of I/U characteristics is already known. However, in most cases, this characteristics is obtained experimentally. Due to the polarity effect the experiment has to be made separately for the positive and the negative polarity of the applied voltage.

2. Phenomenon occurring near a corona electrode

When measuring an I/U characteristics using a point electrode with a positive polarity, higher dispersion of measured current values were detected in a particular voltage area [1–3]. Authors focusing on the area of an audible noise generated by the corona discharge found a tight correlation between the audible noise and the corona current [4]. The polarity effect can also be measured acoustically. Authors [5] showed that the amplitude and the pulse width of the current pulse in positive corona discharge is higher than in negative corona discharge. Further analysis of the time-domain characteristics of corona-generated audible noise pulses [6] showed that with the increase of applied voltage pulse rate increases and amplitudes of the pulses decrease. If the applied voltage is further increased, the pulse rate and the amplitudes of the pulses gradually stay stable.

In general, the current-voltage characteristic of corona processes for both, the positive and the negative polarity, is described as the current steadily increasing with an increase of voltage. This paper shows, that this characteristic is not correct in the case of the point electrode with a positive polarity. The measurements of the current and the light emitted by the corona show that, as the voltage increases, the current first reaches a local maximum, then decreases to a local minimum after which is starts to steadily increase again. This *current-voltage anomaly* in the case of a positive polarity was first observed by prof. Karol Marton in 1980's [7,8]. Under his supervision, Mr. Kapas made a mathematical analysis of the space charge in the weak and strong electromagnetic fields [9,10], where he focused on processes appearing just above the inception voltage of corona discharges. The inception voltage depends on the point electrode end, distance between electrodes and the point electrode material. However, to this date this anomaly has not been studied in greater detail and no methodological experiments were conducted in order to better understand and characterize this anomaly.

Micro-physical processes in a strongly nonhomogeneous field depend on voltage and electric field intensity. Electron avalanches generated in the initial phase are only sporadic. The number of electrons in the avalanche according to Townsend theory increases exponentially. For homogeneous electric field the next equation is valid:

$$n_x = n_0 \exp(\alpha x) \tag{1}$$

where n_x is the number of electrons in the avalanche after reaching the distance x from the cathode, α is Townsend's ionization coefficient. However, in a nonhomogeneous electric field the intensity of electric field $E(x)$ and the ionization coefficient $\alpha(x)$ are not constant. The number of electrons in the avalanche n_x at distance x from the beginning of the avalanche can be calculated as follows:

$$n_x = n_0 \exp\left(\int_0^x \alpha(x)\mathrm{d}x\right) \tag{2}$$

The increase, respectively decrease, of the number of electrons in the space between electrodes is influenced by the following secondary processes:

- secondary cathode electron emission influenced by γ-processes and photo-emission,
- photoionization of neutral molecules of gas,
- collision of ions,
- electron absorption by electronegative molecules e.g. oxygen, water, hydrogen and others,
- electron and ion recombination,
- electron diffusion.

The first three processes contribute to the avalanche electron increase; while the other three processes cause their decrease. Electrons, positive and negative ion are represented unevenly in ionizing fields. The electron concentration can be expressed as [8]:

$$\frac{\partial n_e}{\partial t} = N_i + k_n \alpha_n n_e b_e E - k_a n_e - R_{er} n_+ n_- + \frac{n_-}{\tau} + div(n_e b_e E) + D_e \nabla^2 n_e \tag{3}$$

N_i – electrically charged particle pair number per m^3/s caused by external sources of energy,
$k_n\ \alpha_n\ n_e\ b_e\ E$ – charges generated by impact ionization with b_e mobility and electric field intensity E,
k_n – proportion coefficient,
$k_a n_e$ – electron absorption by particles, where $k_a = \eta_e\ v_e$,
η_e – probability of electron being captured by a particle,
v_e – electron velocity,
n_-/τ - decrease of negative ion density and appear of electrons during τ time interval,
$div(n_e b_e\ E)$ – drift of charge carriers in electrical field,
$D_e \nabla^2 n_e$ – particle diffusion,
$R_{er} n_+ n_e$ – particle recombination.

Positive n_+ and negative n_- ion concentration can be expressed as

$$\frac{\partial n_+}{\partial t} = N_i + k_n \alpha_n n_e b_e E - R_{ir} n_+ n_- - R_{er} n_+ n_e - div(n_+ b_+ E) + D_i \nabla^2 n_+ \tag{4}$$

$$\frac{\partial n_-}{\partial t} = k_a n_e - \frac{n_-}{\tau} - R_{ir} n_+ n_- + div(n_- b_- E) + D_i \nabla^2 n_- \tag{5}$$

Solving these differential equations leads to the density of individual electric charge types that are present in the discharge space. For stationary state it can be shown that:

$$\frac{\partial n}{\partial t} + \frac{\partial n_-}{\partial t} + \frac{\partial n_e}{\partial t} = 0 \tag{6}$$

In strong electric fields the influence of secondary processes has to be considered. By including these factors in the Equations (4)–(6), the overall current density can be expressed as:

$$j(x) = q_e\ [n_+(x) \cdot b_+(x) + n_-(x) b_-(x) + n_e(x) b_e(x)] E(x) \tag{7}$$

Integral current flowing through an area with a diameter S