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# Self-sustaining discharges in needle-to-plane geometry with hundreds of microns electrode gaps

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ABSTRACT

Atmospheric pressure needle-to-plane discharges have been explored experimentally in electrode gaps from 100 μm to 400 μm. These discharges can be self-sustained and follow the form of existing empirical formulae describing the current-voltage characteristics of corona discharge. The discharge can also be self-sustained by its lower sustaining voltage applied between the two electrodes once it is ignited by the initial high output voltage from power supply. The experiments of charging aerosol particles by the self-sustaining discharge operating with a lowered power have shown that for particles with a diameter of 46 nm, the charging efficiency attained 43.6%.

## 1. Introduction

Electrical discharges are the most widely used way to generate low-temperature, non-equilibrium plasmas. Nowadays they are playing a key role in a number of technologies, including electrostatic precipitation [1], plasma displays [2], surface treatment of polymers and textiles [3], and aerosol charging [4]. Recently, there has been growing interest in scaling down plasma devices to hundreds of microns for applications such as small aerosol sensors [5,6], micro-chemical analysis systems [7], and micro-reactors [8]. However, electrical discharge at these small dimensions is not fully understood and only through a deeper understanding can it be optimized for a given application.

Among so many geometries of electrode configuration, needle-to-plane is the most commonly used one (especially for corona discharge) owing to its stable operation in DC mode and the advantage of simplicity. Although steady operation is possible in a wide pressure range for discharges with characteristic lengths of hundreds of microns due to favorable scaling laws, operation at atmospheric pressure is of particular favorable for integration in microsystems and portable devices [9]. Power consumption is another important factor that needs to be considered in the design of discharge components, especially for that to be integrated into to portable devices.

Although millimeter electrode gaps are in the vast majority in the studies of needle-to-plane discharges, continued research on that with micron gaps is also growing. Lee et al. [10] [11] microfabricated a needle-to-plane corona based micromotor whose electrode gap was 50 μm and the sharp electrodes was from 3 μm to 5 μm. The observed onset voltage of sustaining discharge was at 700 V-800 V. Park et al. [12] designed a chip-type needle-to-plane discharger with the inter-electrode gap of 165 μm. The corresponding corona inception voltage was 1.5 kV. Yang et al. [13] [14] and Park et al. [15] used ZnO nanowires as the discharge electrodes to fabricate dischargers. Their experimental electrode gaps were 100 μm and 900 μm and their corona starting voltages were hundreds of volts and 1.6 kV, respectively. Yang et al. [5] [6] employed a tungsten needle to form positive electrode in a gap of 400 μm in the charging units of aerosol sensors. Their initial starting voltage of sustaining discharge was larger than 2 kV. Tirumala et al. [16] explored wire-to-plane corona discharges in electrode gaps from 300 μm to 5 mm and derived a relationship between discharge current and applied voltage.

Despite so many applications of needle-to-plane discharges occurring in micron gaps, there have been very few studies on the characteristics of such discharges. In this work, the authors

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presented an experimental study of needle-to-plane discharges in electrode gaps ranging from 100 μm to 400 μm and the resulting experimental data were compared with existing theories. Reducing the discharge current by using a high-voltage module with limited power and its application in charging aerosol nanoscale particles were also explored.

## 2. Materials and methods

Positive polarity discharges in needle-to-plane configurations were conducted in air at atmospheric pressure. The experimental setup in this study is illustrated in Fig. 1. This system consists of a needle, a copper plane, a source-meter unit (Keithley 2657A), an oscilloscope and two resistors.

Studies on needle-to-plane corona discharges have been revealed that the materials of needles have no measurable difference in corona inception potential or current [17]. Bailey et al. [18] disclosed that the electric field at the tip of the needle depends on tip sharpness, but for tip radii less than 50 μm no further current gain occurs as electrode sharpness is increased, because the discharge becomes so conducting that it shields the electrode tip [19]. In this study, tungsten needle with a diameter of about 26 μm was used as the anode, and the plane is a blank printed circuit board (PCB), which was covered with a layer of 36 μm thick copper and with a diameter of 5 mm. The tungsten needle was inserted into a SMA connector and the insulator in the connector was moved to ensure the alignment between the tip of the needle and the outer edge of the connector. A Teflon spacer with a specific thickness was placed between the connector and the copper electrode to form the discharge gap. The copper electrodes were cleaned using alcohol, acetone and then deionized water ahead of their integration into the system to remove oil and grease, which could maintain nearly the same surface condition of the negative electrodes. Dischargers with five gap distance of 100 μm, 150 μm, 200 μm, 300 μm and 400 μm were fabricated.

The source-meter unit can supply a DC high-voltage (up to 3 kV, 180 W) and measure current (resolution 1 fA, range 120 mA) simultaneously, which was automated via a LabVIEW program to vary the potential and measure the current in a controlled and repeatable manner. Digital current data was also stored through the program. The oscilloscope (internal resistance 10 MΩ) is in parallel with the resistor $R_2$ (1 kΩ) to monitor the occurrence of the self-sustaining discharge. $R_1$ (198.4 kΩ) connected in series with the source-meter unit is a current limiting resistor to protect the unit.

During the experiments, the output voltage from the source-meter unit was increased in increments of 50 V. In order to protect the built-in ammeter from high voltage damage that may occur when the discharge sparks, the measurement function of the source-meter unit was not turned on until the self-sustaining discharge was stable (observed on the oscilloscope), and the maximum output current was set to 11 mA. The current was recorded after it reached a sufficient steady state. All the measurements were made in air at room temperature (23 °C), 760 mmHg of atmospheric pressure and at 26% of relative humidity.

## 3. Theory of needle-to-plane discharges

As the physical mechanism of needle-to-plane discharge is not clear even up to the present, several empirical formulae were suggested to describe the current-voltage characteristics in such discharges. In 1914 Townsend derived a formula to characterize the DC steady corona current-voltage relationship for coaxial cylindrical geometry [20]. Later it was empirically found that the Townsend relation could also be used to approximately describe the characteristics of needle-to-plane geometry [21]. This relation is given as:

$$I = AV(V - V_0), \tag{1}$$

where $I$ is the discharge current, $V$ the supplied voltage, $V_0$ the inception voltage of self-sustaining discharge and $A$ a dimensional constant depending on the inter-electrode spacing, the needle electrode radius, the charge carrier mobility in the drift region and other geometrical factors.

Yamada [22] carried out a series of measurements with a point-to-grid electrode geometry. His results indicated that the current-voltage characteristics of this type of discharge roughly obey Townsend's relation, in which coefficient $A$ is proportional to temperature for a particular electrode gap. So he modified the Townsend relation by considering the influence of ambient temperature and of inter-electrode spacing, obtaining an empirical formula of the form of

$$I = C_1(T - 132)S^{-2.8}V\left(V - C_2T^{-1}S^{0.39}\right), \tag{2}$$

where $C_1$ and $C_2$ are coefficients depending on the electrode geometry, $T$ the ambient temperature with a Kelvin scale and $S$ the inter-electrode spacing.

Ferreira [23] proposed another empirical relation referred to as

$$I = B(V - V_0)^2, \tag{3}$$

where $B$ is also a dimensional constant.

In 1980 Henson [24] theoretically derived a mathematical model for microscopic point-to-plane discharges in the steady-state regime, which is expressed as

$$I = (2\pi K\varepsilon/\alpha)(F(\delta/\alpha))^{-2}(V - V_0)^2, \tag{4}$$

where $\delta$ is the minimum glow radius, $\alpha$ the spacing between the needle tip and the plane, $K$ a dimensional constant and $F(\delta/\alpha)$ a polynomial function.

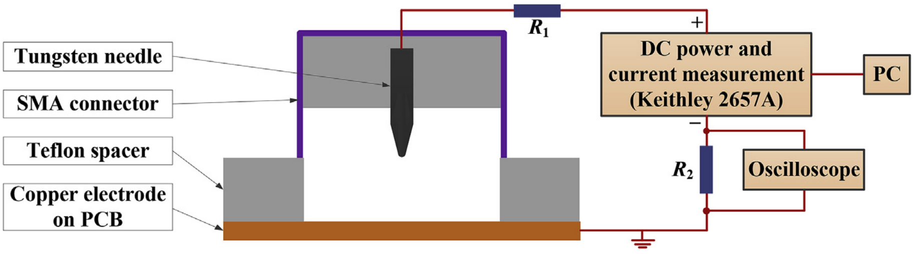

**Fig. 1.** Schematic diagram of the measurement system.