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Analysis of geometric scaling of miniature, multi-electrode assisted corona discharges for ionic wind generation

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ABSTRACT

The assisted corona discharge is a unique discharge configuration that utilizes multiple collecting electrodes to minimize the voltage required to initiate a corona discharge and to generate an ionic wind. In this work, the geometric parameters that govern the formation of the assisted corona discharge and subsequent ionic wind are evaluated. Flow velocity measurements suggest that the geometry of the electrode spacings is optimized for ionic wind generation when the current flowing to the collector electrode is maximized, and that as the electrode gap is decreased to microscale dimensions, ionic wind production is inhibited.

Introduction

As atmospheric-pressure plasmas and discharges have grown in popularity, a number of unique discharge configurations have been proposed. One of the most intriguing areas is the development of novel multi-electrode configurations that serve to manipulate the discharge in non-traditional ways, either to stabilize or extend the discharge. Conventionally, discharges are generated between two electrodes (cathode and anode), but many of these multi-electrode configurations employ a third electrode (three-electrode configuration) to extend or extract an additional discharge beyond the primary discharge region. A variety of multi-electrode discharge configurations exist [1–6], and one of particular interest is the multi-electrode corona discharge [6] as shown in Fig. 1.

One of the by-products of discharges is an induced electrohydrodynamic flow or ionic wind, where the collisions between accelerated ions and neutral gas molecules results in a bulk flow. Both surface dielectric barrier discharges (DBDs) and corona discharges are often used for ionic wind production [7,8], and in our prior work, we demonstrated that this multi-electrode corona discharge configuration generated a higher flow rate than a conventional two-electrode configuration at the same applied potential [6]. The primary cathode served as a gate electrode that initiated the discharge, but additional discharge current flowed to the second (collector) cathode, resulting in essentially two independent discharge beams. Current measurements showed that similar behavior occurs with both positive polarity coronas (with multiple cathodes) as well as negative polarity coronas (with multiple anodes), and Fig. 1b shows a photograph visualization of the discharge in negative corona mode. Importantly, the two discharge beams were initiated simultaneously at a single onset voltage that was dictated solely by the gate electrode, hence it has been termed an assisted corona discharge as the gate electrode assisted the formation of a discharge to the second cathode. This allowed the discharge to be generated at a lower voltage than if the gate electrode was absent, and in this configuration greater flow rates were produced at lower operating voltages.

The increase in flow generation at lower operating voltages is attractive for ionic wind applications in heat transfer and fluid dynamics. While operating at lower voltages simplifies the electronics needed to drive the ionic wind overall, for a number of applications, especially those involving portable devices, there are also practical limitations on the magnitude of the operating voltage

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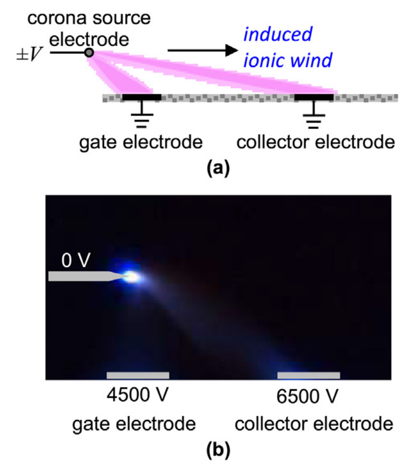

Fig. 1. (a) Schematic of a direct current (DC) assisted corona discharge with two distinct collecting electrodes (primary and secondary) [6]. The corona source can be operated at different polarities to form a positive or negative discharge, respectively. (b) Photograph image of assisted corona discharge operated in negative DC mode. The corona source was a needle operated as the cathode and the two collecting electrodes were flat plates operated as a primary and secondary anode.

and the high-voltage power supply. Thus it is necessary to explore electrode configurations that reduce the operating voltage without adversely affecting ionic wind generation. However, fundamental study is required to more completely understand the behavior of the assisted corona discharge in order to optimize design and increase ionic wind efficacy.

Corona discharges, in general, are dependent on the geometry of the electrodes and stabilized by forming a highly inhomogeneous electric field in order to localize the region where the electric field exceeds the breakdown threshold (~3 V/μm for atmospheric air). This inhomogeneous field is formed by a sharp electrode with small radius r_0 relative to the electrode gap distance d, and Peek predicted that in a nominal point-to-plane configuration, these geometric parameters must be $d/r_0 \geq 2.925$ in order to ensure sufficient inhomogeneity in the electric field to maintain a stable discharge [9]. Likewise, the current–voltage relationship in a corona discharge (often called Townsend's relationship) is also heavily dependent on these geometric parameters, as the charge transport is dominated by a nearly-Laplacian electric field [10]. It is therefore intuitive that the behavior of the assisted corona discharge will also be heavily dependent on the geometric parameters of the configuration, and it is therefore necessary to understand how these geometric parameters influence operation and ultimately, ionic wind production.

In this work, we conduct an experimental investigation on the influence of geometric parameters on assisted corona discharge formation and ensuing ionic wind production. Specifically, we aim to understand the miniaturization of assisted corona discharges to scales approaching microscale dimensions. The miniaturization of corona discharges is an area of growing interest [11], as recent advances in microfabrication have enabled the development of a wide variety of devices [12–15] that could potentially be used in portable technologies. In our prior work, we demonstrated that one advantage of the assisted corona discharge is that it promoted the stable operation of corona discharges in narrow ducts, where the confined geometry often disrupts the inhomogeneity in the electric field. While others have investigated multi-electrode discharges at larger scales [16–21], in this work we look at extreme scales of operation (~100–1000 μm) and establish microscale limits on the benefits of the assisted corona discharge and its application to ionic wind generation.

Experimental method

A schematic of the test configuration is shown in Fig. 2 where a positive assisted corona discharge was created between a needle (the corona source) and two adjacent electrodes. The corona source was a tungsten microneedle with a tip radius of $r_0 \approx 1.5$ μm. The gate electrode was a coaxial copper cylinder of width $w = 1$ mm surrounding the corona source such that the gate distance d corresponded to the radius of the cylinder. The collector electrode was a thin (3 mm diameter) vertical copper cylinder downstream of the corona source a distance D. The specific geometry for the gate and collector electrodes was based on a number of preliminary studies to determine a suitable configuration for a scaling study and ionic wind generation. The circumferential configuration for the gate electrode ensured a uniform electric field surrounding the corona source, increasing overall current production and ionic wind generation, and the thin downstream cylinder limited flow blockage and allowed for downstream flow. The gate electrode was positioned using a camera with a 100 mm macro lens to assure the corona source was properly centered within the gate electrode. To mitigate the effects of impurities on the needle tip, the needle was regularly washed with acetone between measurements. If data taken from subsequent measurements varied greatly from previous measurements, the needle was replaced.

The goal of this study was to understand the effect of geometric parameters on the formation of an assisted discharge and subsequent ionic wind production. To vary d from 0.25 to 1.0 mm, different gate electrodes were fabricated with different radii, and to vary D from 0.25 to 4.0 mm, the position of the corona source was varied by a mechanical micropositioner. The two electrodes (needle and cylinder) were initially brought gently into contact, creating a closed circuit. The needle was then backed off slowly until the contact was broken. This transition was noted by the application of a small voltage (~5 V) and observing the drop in current at contact separation. The source was then moved a distance, D, from the collector electrode. These scales, on the order of 100–1000 μm, represent some of the smallest corona discharges reported to date [11]. However, discharges below 250 μm were not possible without directly sparking.

The assisted corona discharge was operated in direct current (DC) mode, and a schematic of the electrical circuit is also shown in Fig. 2. A high voltage DC power supply (Bertan 225) was connected to the corona source. The circuit was grounded to a hard-wired earth ground within the laboratory. Current measurements at the gate and collecting electrodes were made with two independent picoammeters (Keithely 6485). For a fixed D and d, the voltage

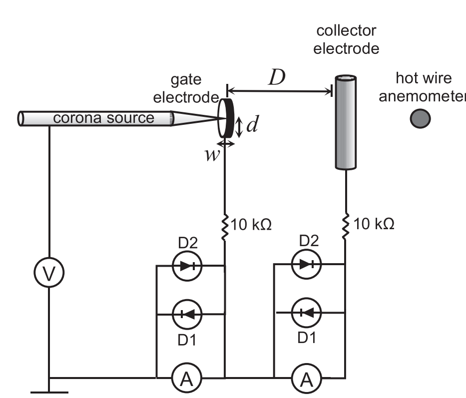

Fig. 2. Schematic of the experimental setup, including the relevant geometric parameters and the electrical circuit.