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Dual-pin electrohydrodynamic generator driven by alternating current

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ABSTRACT

We report a unique alternating current (AC) driven corona based air-flow generator using symmetrically arranged electrodes. Unlike the conventional configuration where one electrode generates charged ions moving towards the reference electrode, this configuration allows both negative and positive charges to simultaneously move away from the device and generate ion wind in parallel with the electrodes. In comparison with the direct current (DC) driven corona generator, the time oscillating AC field allows the device a better stabilization owing to the independence of ion wind strength from the inter-electrode spacing. Our results by both simulation and experiment showed that when the AC frequency exceeds a threshold value of 1100 Hz, the electric field at the electrode tips is determined dominantly by the charge cloud created in the previous half-cycle, resulting in stronger net electric field and thus stronger ion wind. In addition, the electrode separation in the AC driven corona based generator is less critical above the frequency threshold, yielding a more robust design with minimized susceptibility to manufacturing tolerances and impurities on the electrodes. Moreover, lower voltage levels of the AC driven system allow simpler and more economical design in the high voltage circuit of the AC generator.

1. Introduction

Electric field driven air flow requires the accelerated charged particles to transfer their momentum to the surrounding neutral particles. A widely-used configuration for generating air flow utilizes ionization by gas discharge, where strong electric field capable of ionization is generated nearby a suitable electrode. The ions accelerate in the electric field and collide with neutral air molecules, resulting in momentum transfer represented by volumetric electrohydrodynamic force, which gives rise to bulk air movement commonly called as ion wind. The ion wind has been used in various airflow control applications [1–3], cooling application [4–7], propulsion technology [8–10], micro-pump design [11,12], precipitation filtering [13,14], and electronic devices [15–17]. There are several methods generating electric-field driven ion wind and two principal approaches are reviewed below.

For the direct corona discharge (DCD) method, ion wind is generated by the direct discharge from one electrode to another one. The fundamental requirement for a conventional corona discharge includes a high-curvature electrode where ions are generated, and a reference electrode of low-curvature directing the movement of charged particles (Fig. 1a). The discharge mechanism of the positive and negative coronas is different and the resulting discharge is dependent on the polarity of the electrical field and the geometrical configuration of electrodes. For this approach, various electrode configurations have been published, including point-to-ring [18–21], point-to-plane [22–26], point-to-grid [27–30], or wire-to-plate [31–33]. Recent works have shown further improvements on ion wind generation, including the use of alternating negative/positive discharge [34,35], multiple electrodes [36], and multiple stages [37,38]. Since this method uses DC driven static electric field, the discharge ion current and the space charge need to be compensated in the downstream space to prevent the charging of the device [39,40].

Another widely used approach for creating ion wind is the dielectric barrier discharge (DBD). For this approach, the configuration usually consists of two electrodes separated by an insulating dielectric barrier to prevent sparking. Thus, it can be considered as the indirect discharge method [41] (see Fig. 1b). In the DBD, the charge generated from one or both electrodes quickly accumulates on the dielectric surface. This reduces the net electric field and stops the process of ion generation [42]. Many different electrode configurations have been introduced, such as

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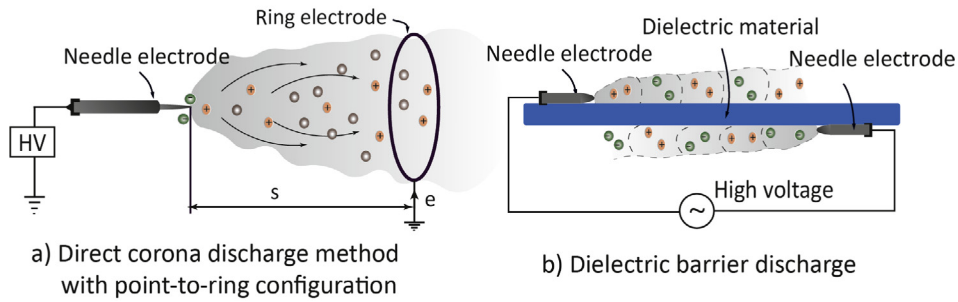

Fig. 1. Mechanism of ion wind generation: (a) DC driven Direct Corona Discharge (DCD) method with point-to-ring configuration; and (b) AC driven Dielectric Barrier Discharge (DBD) method.

wire-dielectric-wire [43] and ring-dielectric-ring, with time-varying applied voltage to ensure that the accumulated charge is neutralized and the discharge is periodically restarted. The scaling law for this type of discharge has been established [44] together with the effect of governing parameters such as voltage and ambient gas [45,46]. Since the discharge is generated by AC voltage, the DBD produces a pulsed wind that oscillates with a frequency twice of that of the driving signal. This approach usually generates two similar ion winds with opposing charges in a time period, and therefore the DBD may also be referred to as the bipolar discharge method.

While the force by electric field directs the charge from one electrode to another one in the DCD based system, the electric force in the DBD applied system varies with respect to the direction of electric field and intuitively yields a zero resultant force. However, several research works pointed out that the transient migration of charged species within the AC field increases the net ion wind [47]. Over the last two decades, many publications on corona discharge driven by AC have shown some interesting results. For example, Kim et al [48] observed that the onset voltage in DCD was 10–20% lower than that of the DC regime using wire-to-half ring configuration, and the effect of AC on the increase of ion wind was noticed in the range of frequencies 2000–3000 Hz. Meanwhile, using the point-to-ring configuration, ion wind reached a peak value in the range of frequencies 500–1000 Hz and 200–2300 Hz by Ohyama et al [49,50] and Drews et al [21], respectively.

The difference in the mechanism of above two methods results in the different ion wind characteristics. The stationary electric field in DCD generates ion wind of only positive or negative charge. On the other hand, the transient electric field in DBD generates two ion winds of opposing charges for its pair of symmetrical electrodes. However, despite generating two ion winds of opposing charges, only one of them can be used at any one time because of the opposing direction of the ion wind movements.

In this paper, we present a hybrid configuration of ion wind corona discharge where a pair of electrodes arranged in parallel connects to an AC power as described in Fig. 2. The presented configuration is a further development expanding on our recent work [51–57] and possesses several configurational characteristics of DCD and DBD approaches. This configuration allows both negative and positive charges to simultaneously move away from the device in the same direction in parallel with the electrodes, and generate ion wind for both constant and transient applied voltages. In particular, experimental results show that the effect of AC in this configuration creates an ion wind flow independent of the electrode separation. For the system characterization, the correlation of ion wind with electrode separation, AC voltage and frequency are presented using experiments and numerical simulation. The effect of charge movement on the discharge operation and the generated ion wind are also discussed.

2. Mechanism and experimental setup

The mechanism of bipolar discharge using parallel pin electrodes driven DC high voltage has been established and described in our previous publications [51,52]. In the DC based regime, the flows of oppositely charged ions generated at the electrode tips impinge on each other and recombine within the inter-electrode space, create a steady ion wind flow. The electrode separation is a governing parameter of this regime because it allows to determine the impact angle of the oppositely charged flows as well as the corona generation due to electric field strength at the electrode tips, therefore defining the total wind flow. The mechanism of DC driven bipolar discharge is schematically described in Fig. 3a.

Our experiment showed that the mechanism of AC driven bipolar discharge at low frequencies is not different from the DC driven system as described by the schematics in Fig. 3b. With low switching frequencies the space charge has sufficient time to diffuse and its additional effect is negligible in time scales compared with the switching frequency. On the other hand, the accumulated space charge plays a significant role when the AC frequency increases. The ion cloud becomes more localized because of the recombination with the ions generated in the previous half cycle. As described in Fig. 3c, for a given polarity, charge is generated similarly as in DC regime, subsequently moving away from the electrode under the influence of the electric field. When the polarity changes, the opposite charge from the previous half-cycle will exert an additional electrostatic force. This additional electric field increases with increasing frequency until it overcomes the electric field defined by the opposite electrode, and at this stage the electric field driving the ion wind becomes independent of the electrode separation. Intuitively, it can be seen that there is a limit to the enhancement of the electric field and subsequent ion wind generation by increasing frequency. At even higher frequencies, where the time of ion drift between the electrodes is comparable with the half cycle of the applied frequency, the corona discharge is not fully created and the ion cloud is not generated.

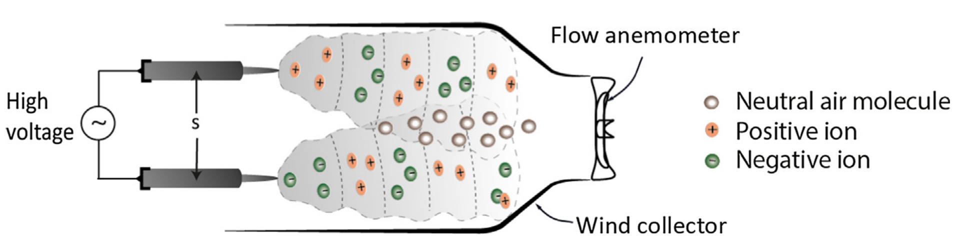

Fig. 2. AC driven bipolar discharge method using symmetrical electrode configuration: ion wind generated at each electrode in accordance with the applied AC voltage.

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