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Enhancement of thin air jets produced by ring-shaped dielectric barrier discharges using an auxiliary electrode

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ABSTRACT

A ring-shaped dielectric barrier discharge (DBD) was explored as a small form factor ionic wind device. Using a concentric ring electrode geometry, the DBD produced a converging ionic wind that leads to a vertical flow away from the DBD electrodes. The vertical flow was channeled through an outlet nozzle to produce a thin air jet, and a grounded auxiliary electrode was placed at the nozzle to enhance the exit velocity. The inner diameter of the ring-shaped DBD electrode and the auxiliary electrode ranged 3.18–9.54 mm and 1.0–4.0 mm, respectively. Results showed that the auxiliary electrode generated an ionic wind velocity up to 3.7 m/s and increased the conversion efficiency from discharge to flow power by a factor of 30 by strengthening the electric field where the ions are accelerated.

1. Introduction

Ionic winds (also referred to as electric winds or electrohydrodynamic flows) are bulk air flows generated by applying a large electric field between two electrodes in air to breakdown the interstitial gas and create a discharge. The discharge produces gas ions that are accelerated by an electric field, where their numerous collisions with neutral gas atoms and molecules leads to a bulk flow. Devices that drive bulk flows using an electric field have several advantages over conventional air movers, most notably their silent operation, rapid response time, and lack of moving parts. These advantages have led to interest in integrating them in various fields, including the control of boundary layer separation from airfoils [1–3], as electrostatic precipitators [4–8], and for the enhancement of convective heat transfer [9,10]. Ionic wind devices are generally classified by the type of discharge that produces the flow – a corona discharge [3–17] or dielectric barrier discharge (DBD) [1, 2, 18–26] – and reference [27] provides an extensive review of the field. This study focuses on a DBD generated with ring-shaped electrodes [26] to produce thin air jets for applications such as electronics cooling.

Over the past few decades, electronic devices have rapidly decreased in size. This miniaturization of electronic devices has produced the need for new thermal management strategies that can provide highly localized cooling at locations of high heat flux within the device. To fill this role, the thermal management solution needs to conform to strict geometric constraints to operate in these platforms while also producing a significant amount of flow. A ring-shaped DBD can generate high velocity air jets at the center of the ring, making it a compact method for flow generation. The small size of such a DBD device would allow for easy integration into miniature electronic platforms, and could be a promising candidate for localized cooling in miniature electronic devices. In particular, the fast and small air jets produced by the DBD may be more suitable for cooling specific spots, so-called "hot spots," as opposed to uniform air flow generation like a mechanical fan. Although there are challenges with incorporating DBD ionic wind devices into electronics applications, including shielding issues and problems with ozone and similar byproducts, many of these are addressable if the ionic wind device can provide sufficient cooling capability.

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In this study, we explore the impact of placing grounded auxiliary electrodes above the center of the ring-shaped DBD to determine its effect on the air jet's speed and flow rate. Recently, it has been shown that including auxiliary electrodes downstream of the discharge-producing electrodes can enhance airflow by essentially extending the active area for the Coulombic body force of the discharge [13–15]. The auxiliary electrode was put in place to enhance the local electric field to pull more flow through the ring outlet. The performances with and without grounding the auxiliary electrode were compared to determine the extent of the grounding electrode's impact.

2. Experimental methods

Fig. 1 shows a schematic of the flow generating device tested in this study. As illustrated in Fig. 1(a), the basic structure consisted of a circular plastic substrate, containing DBD electrodes, and a plastic disk, referred to as the lid, with an opening at its center placed above the plastic substrate. The DBD was generated by ring shaped electrodes to produce surface DBDs on the plastic substrate. These surface DBDs produced an ionic wind pointed radially inward along the surface of the plastic substrate. At the center of the plastic substrate and ring electrodes, the radially inward ionic wind converged and was redirected perpendicular to the substrate. This orthogonal air flow was accelerated through an outlet nozzle in the lid to produce an air jet.

The exact geometry and dimensions of the ring-shaped DBD jet unit are shown in Fig. 1(b). Basic structures were produced with a

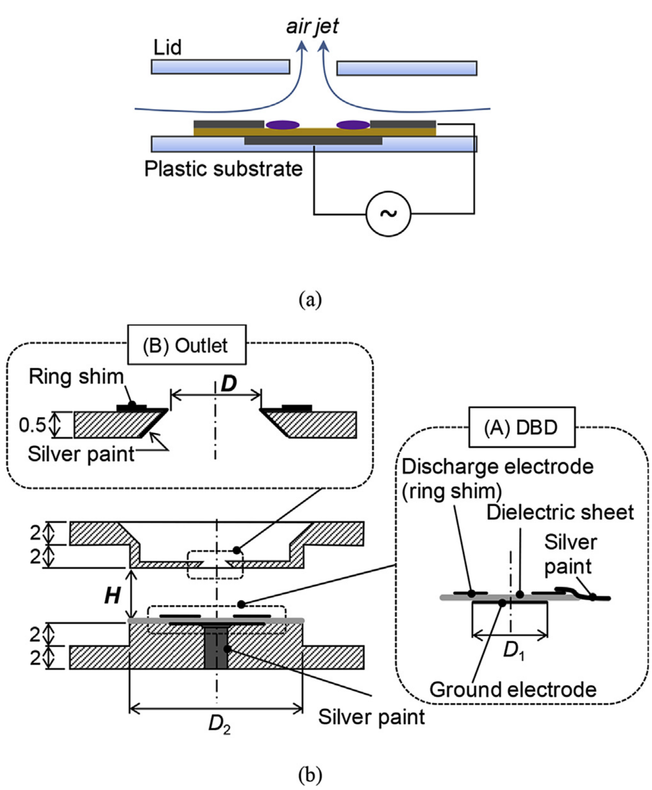

Fig. 1. (a) Illustration showing ionic wind air jet produced by ring electrode DBD. (b) Schematics of ring-shaped DBD jet unit. The DBD electrodes shown in Inset A are placed on top of the plastic substrate, and the silver paint electrical terminal makes contact with the ground electrode. The lid is positioned at a height H above the DBD and airflow coming radially inward produces an orthogonal vertical jet that is directed through the outlet. As shown in Inset B, the outlet includes an auxiliary electrode to help promote a stronger ionic wind through the outlet. All units are in mm.

3D-printer (Fortus 250 mc from STRATASYS Ltd., printed plastic: ABSplus). The DBD was generated on the surface of the plastic substrate. A grounded electrode made from copper foil with a thickness of 0.0381 mm and a diameter D_1 was placed on the top surface of the plastic substrate (as shown in the inset), and an electrical terminal made from silver conductive paint (5001-AB, SPI Supplies) passed through the bottom of the plastic substrate to make contact with the grounded electrode. Three sheets of polyimide (Kapton adhesive tape with a thickness of 0.0254 mm from DuPont) with diameter D_2 were used to cover the grounded electrode and acted as the dielectric layer. Finally, a stainless-steel ring-shim with a thickness of 0.0381 mm was attached on top of the polyimide and used as the discharge electrode. Three different sets of electrodes (types 1–3), each of which has unique diameters, were used and are summarized in Table 1.

The lid was 0.5 mm thick and placed a distance H from the plastic substrate, referred to as 'duct height' in this report, that was varied from 0.5 to 3.5 mm. The outlet nozzle had a diameter D (as shown in the inset) that was varied from 0.5 to 4.0 mm, and the opening was at a 45° taper. The inner surface of the taper was painted with silver paint which was electrically connected to a ring-shim that had 3.18 mm inner and 4.76 mm outer diameters placed on the top surface of the lid. The ring-shim worked as an electrical terminal. In the case where the outlet diameter was $D = 4.0$ mm, the electrical terminal was made from silver paint alone. When the test was conducted to find its nozzle effect without grounding, the lid that was not provided with the outlet electrode was used.

Fig. 2 shows the electrical circuit used to generate the DBD and the apparatus used to measure flow velocities. A sinusoidal AC high voltage at 20.8 kHz generated by a power supply (Model PVM500, Information Unlimited) was used to drive the discharge. Note that the choice of frequency was dictated primarily by power supply availability, and optimization of the frequency will be needed in future work. The current through the DBD electrodes from the AC power supply (i_{dbd}) was detected with a current probe (Model 4100, Pearson Electronic) and the current through the auxiliary electrode at the outlet of the lid (called 'auxiliary current', i_{aux}) was measured by inserting a 3.6-kΩ-resistor in the circuit. In cases where the auxiliary electrode at outlet was grounded, a copper needle was put on the ring-shim illustrated in the enlarged view of Fig. 1(b). The needle connection had minimal influence on the flow and electric field. The power consumption of the DBD (P_{dbd}) and that through the auxiliary current (P_{aux}) were found by time-integrating the products of the applied AC voltage and the currents i_{dbd} and i_{aux}, respectively.

To measure the local velocity v at the center axis of the outlet, the tip of a pitot-static tube was placed 0.5 mm above the top surface of the lid on the center axis of the outlet. The pitot-static tube was electrically floated. The outer diameter of the pitot-static tube and the diameter of the opening at its tip were 2 mm and 0.48 mm, respectively. The pressure differences between a total pressure and a static pressure were detected with a pressure sensor, from which velocities were calculated using Bernoulli's theorem.

In addition to velocity, the flow rate Q of the ionic wind at the outlet was measured with a flow bench apparatus illustrated in Fig. 3. This was based on the same principle as that described in Ref. [17]. The entire DBD flow unit shown in Fig. 1 was attached to the end of the plastic chamber, which had a straight duct of 80 mm in inner diameter and 110 mm in length. This chamber was connected to a vacuum source installed in the laboratory. The suction flow rate was adjusted with a needle valve so that the suction canceled the increase in static pressure caused by the ionic wind. When the pressure in the chamber matched atmospheric pressure, the flow rate of the suctioned air was considered the same as the