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Corona based air-flow using parallel discharge electrodes

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ABSTRACT

A novel air-flow generator based on the effect of ion wind has been developed by the simultaneous generation of both positive and negative ions using two electrodes of opposite polarity placed in parallel. Unlike the conventional unipolar-generators, this bipolar configuration creates an ion wind, which moves away from both electrodes and yields a very low net charge on the device. The electro-hydrodynamic behavior of air-flow has been experimentally and numerically studied. The velocity of ion wind reaches values up to 1.25 m/s using low discharge current 5 μA with the kinetic conversion efficiency of 0.65% and the released net charge of −30 fA, 8 orders of magnitude smaller compared with the discharge current. Due to easy scalability and low net charge, the present configuration is beneficial to applications with space constraints and/or where neutralized discharge process is required, such as inertial fluidic units, circulatory flow heat transfer, electrospun polymer nanofiber to overcome the intrinsically instability of the process, or the formation of low charged aerosol.

The principle of ion wind generation using corona discharge was systematically described in 1899 by Chattock with needle-to-plate and needle-to-ring configurations [1]. However, this phenomenon had not achieved active progress until Robinson [2] modeled ion wind generation to calculate the kinetic energy conversion using coupling electro-mechanical parameters. Indeed, many publications reported the characteristics of various electrode arrangements including point-to-plane [3], point-to-grid [4], point-to-ring [5], wire-to-plate [6], wire-to-incline wing [7], where ion wind is generated from a thin wire/needle with high curvature, yielding high velocity of ion wind near the surface of the collector electrode. Many other developments of this method using needle-to-parallel plates [8], point-to-wire [9], rod-to-plate [10], point-to-parallel plate [8], wire-to-cylinder [11], wire-to-wire [12], or point-to-cylinder [13] have been recently suggested. Furthermore, several geometrical improvements of electrodes have also been reported to optimize ion flows by using alternating negative/positive [14], multi electrodes [15].

Ionic winds are most widely used to enhance the heat transfer effect of external flow and a comprehensive review can be seen in the work of Wang et al. [16]. In the above systems, one kind of charge particle is dominant and the fundamental requirements is a high-curvature electrode that generates ions and a low-curvature reference electrode placed downstream to define the movement of particles. The discharge ion current and space charge need to be compensated by electrons in the downstream space to eliminate the charging of device [17]. This is sometimes considered as a drawback and a dual positive and negative plasma thruster was proposed to avoid the need for additional neutralization of the system [18], which indeed requires a special electronic power source.

In this paper, a generator of ion wind has been developed using a unique bipolar discharge configuration whose electrodes are symmetrically arranged (Fig. 1). For this configuration, two electrodes of opposite polarity are placed in parallel and generate ions. Hence, both electrodes serve as emitters as well as reference electrodes for generating electric field. This is principally different from multi actuator designs powered from different power sources, providing not only cost savings due to single power source, but also enabling a charge-balanced design with simultaneous charge neutralization in the free space [19]. It is also distinguished from, for

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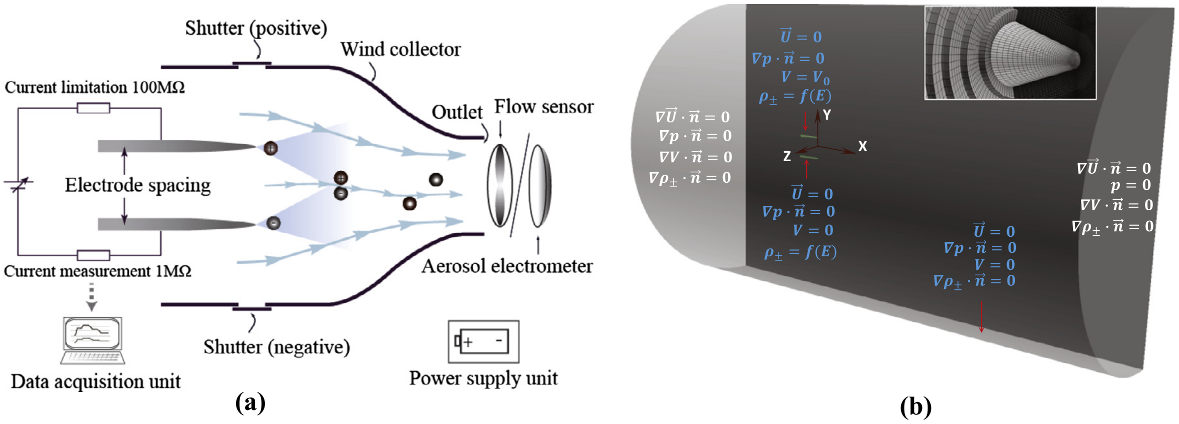

Fig. 1. Bipolar discharge ion wind generator. (a) Experimental setup. (b) Numerical simulation model, a cylindrical domain with diameter and length of ten and twenty times of electrode separation; the inset shows magnified view of mesh at pin tip.

example, a typical needle-to-ring configuration where the neutralization occurred at the reference electrode. The results by our experimental work as well as numerical simulation showed that due to the modified configuration, the ion movement is controlled to be parallel with the axes of the electrodes and away from the device. Because of the high recombination rate of ions [20], the net charge released is very low. Due to easy scalability and low net charge, the present configuration is beneficial to applications with space constraints and/or where neutralized discharge process is required, such as inertial fluidic units [21], circulatory flow heat transfer [22], electrospun polymer nanofiber to overcome the intrinsically instability of the process [23], or the formation of low charged aerosol [24].

The experimental set-up is installed using two identical stainless steel SUS304 pins, each 8 mm long and 0.4 mm in diameter, and placed in parallel as shown in Fig. 1a. Two different kinds of spherical radius (SR) of tips are 15 μm and 80 μm are selected to investigate the effect of pin geometry. The distance between pins is adjustable with a resolution of 0.1 mm using a three axis movable stages TSD-40DC (OptoSigma). A high voltage direct current generator Kopell10 (Kyoshin Denki) is used. A nano-ammeter is also integrated in the voltage generator to measure the discharge current at negative electrode. In order to ensure that the negative charge is accurately measured at the negative polarity and represents the mirror image of positive charge, the entire device is battery operated and insulated from surroundings. The power supply is calibrated using DHM-20 system (Finechem), for a range 0–10 kV.

In order to determine the charge and velocity of the generated ion wind, an aerodynamically shaped collector of 25 mm length, 30×30 mm^2 inlet gate and 15×15 mm^2 outlet gate is used as shown in Fig. 1a. The ion wind is measured by a thermal anemometer ISA-90 N (Sibata) installed 10 mm downstream from the outlet gate of the collector. The released charge is alternatively measured at three positions: positive side shutter, negative side shutter and outlet gate, using an aerosol electrometer 3068 (TSI) with sampling rate of 1 Hz. The measurements were performed in steady state discharge condition, verified by monitoring the discharge current throughout the experiment, All the measurements were carried out at 22 °C, 55% of relative humidity in atmospheric pressure, the surrounding air is filtered by HEPA filter to minimize background charge and the upstream velocity of the system ambience is always kept under 0.04 m/s. For air movement visualization, smoke is introduced from shutters and the flow is observed by a high-speed camera at a frame rate of 250 fps.

For electro-hydrodynamic simulation, we assume that ion wind is an incompressible turbulent flow of ions and the plasma region, where the gas is ionized in the vicinity of the electrode tips, is modeled by the corresponding charge density. In steady state, the model describing migration of ions within inter-electrode region, their mutual influence on electric field and the charge consumption from recombination process are governed by equations of Gauss' law of electrical field and the conservations of charge, momentum and mass

$$\nabla\cdot\vec{E} = \nabla\cdot\nabla V = -(q_+ - q_-)/\epsilon_0, \tag{1}$$

$$\nabla\cdot(\pm\mu q_\pm \vec{E} + q_\pm \vec{U}) = \mp R_i q_+ q_-/q_e, \tag{2}$$

$$\nabla\cdot(\vec{U}\,\vec{U}) - \nu\nabla\cdot(\nabla\vec{U}) = (q_+ - q_-)\,\vec{E}/\rho, \tag{3}$$

$$\nabla\cdot\vec{U} = 0, \tag{4}$$

where $\epsilon_0 = 8.854 \times 10^{-12}$ CV^{-1} m^{-1} is the permittivity of free space; $\mu = 1.6 \times 10^{-4}$ m^2 V^{-1} s^{-1} is the mobility of charge; $R_i = 10^{-13}$ m^3 s^{-1} is the rate constant for ion-ion recombination in air; $q_e = 1.62 \times 10^{-19}$ C is the charge of electron; $\rho = 1.2041$ kg m^{-3} and $\nu = 15.7 \times 10^{-3}$ m^2 s^{-1} are the density and kinematic viscosity of the air, respectively.

It is worth noting that the mutual effects of the electrical field to the ion wind velocity are expressed by $\mu q\,\vec{E}$ and $q\,\vec{U}$ where q, $\vec{E}$, $\vec{U}$ are the charge density, electric field strength and the ion wind velocity, respectively. Neglecting any external bulk flow and the ion diffusion, the charge drift creates an electric current density $\vec{J} = \vec{J}_+ + \vec{J}_-$, satisfying the continuity condition $\nabla\cdot\vec{J} = 0$. Eqs. (1)–(4) were discretised in 3-dimensional space using the far field boundary condition as shown in Fig. 1b. The voltage is applied on the boundary of the electrodes. The charge density condition is computed from the experimentally measured current $q_\pm = I/(\mu E_{on} A)$, A is the total area on the electrode where the electric field is greater than corona onset determined by Peek's law for air $E_{on} = 3.23 \times 10^6$ V m^{-1}. For the velocity of ion wind, the wall condition is non-slip at the electrodes and zero pressure is at the others. The numerical simulation of the problem was carried out using an in-house code developed from OpenFOAM library.

Fig. 2a presents two typical relationships between the voltage and current ($I/V \propto V$ (the Townsend relation) and $\sqrt{I} \propto V$) using the present configuration with electrode spacing of 6 mm and pin tips SR = 15 μm. As can be seen, while the relationship $I/V \propto V$ is non-linear (concave upward), a linear behavior was observed for $\sqrt{I} \propto V$ over the whole measured range of the voltage except at very low current.