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Bipolar corona discharge based air flow generation with low net charge

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ABSTRACT

In this paper, we report on a miniaturized device that can generate ion wind flow with very low net charge. Both positive and negative ions are simultaneously generated from two sharp electrodes placed in parallel, connected to a single battery-operated power source. The two-electrode arrangement is symmetrical, where the electrode creating charged ions of one polarity also serves as the reference electrode to establish the electric field required for ion creation by the opposite electrode, and vice versa. The numerical simulation is carried out with programmable open source OpenFOAM, where the measured current-voltage is applied as boundary condition to simulate the electrohydrodynamics flow. The air flow inside the device is verified by eight hotwires embedded alongside the downstream channel. It was confirmed that the jet flow generated in the channel has a linear relationship with the square root of the discharge current and its measured values agree well with simulation. The device is robust, ready-to-use and minimal in cost. These are important features that can contribute to the development of multi-axis fluidic inertial sensors, fluidic amplifiers, gas mixing, coupling and analysis. The proposed configuration is beneficial 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 intrinsic instability of the process, or the formation of low charged aerosol for inhalation and deposition of charge particles.

1. Introduction

Flow is known as a vital aspect in the function of microfluidic devices. Flow generators are essential for any microfluidic system and have been an attractive topic of research for decades [1]. Depending on the working principle, flow generators can be classified into displacement type and dynamic type [2] categories, which distinguishes the reciprocating and the continuous flow [3]. In terms of geometry, an additional classification separates these devices into categories with and without a check-valve, or further classification is based on the design parameters, such as the size, rate, and power density [4]. In parallel with advancements in micro technology, micropumps especially valveless pumps usually cover a hybrid study in conjunction with jet flow generation. This inherently made piezoelectric lead zirconate titanate (PZT) as the most commonly used actuator for valveless displacement type because of its small stroke volumes, large natural frequencies and commercial availability [5–10].

Another way to create jet flow is by electrokinetic actuation. Under a strong electric field, every charged particle is subjected to Coulomb force and while accelerated by the field, the charge particles collide with neutral fluid molecules, transferring momentum which results in fluid drift. The sum of Coulomb forces is called the volumetric electrohydrodynamics (EHD) force. This principle can be applied upon either the existence of space charge in the fluid such as ion injection pumping from corona discharge [11], conduction pumping for weak electrolyte [12], induction pumping for surface charge in a dielectric [13], or Maxwell pressure gradi-

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Nomenclature

$\vec{E}$	Electric field
V	Discharge electric potential
q	Charge
$\rho_\pm$	Charge density
$\vec{J}$	Electric current density
S	Distance between electrodes
A	Effective area of electrode tip
ε_0	Permittivity of free space
μ	Mobility of charge
R_i	Ion recombination rate
ρ	Air density
U	Flow velocity
d	Distance from electrode tip to hotwire
I_{hw}	Heat current for hotwire
R_{hw}	Hotwire resistance
α	Temperature coefficient of the resistance
A_{hw}	Surface area of hotwire
V_{hw}	Output voltage on hotwire

ent for electro-conjugate fluid [14]. For air pumping, the result of the momentum transfer is a bulk air movement commonly called the ion wind, and it has recently attracted more interest as it features several advantages: low weight, simplicity, robustness, lack of moving parts, and low power consumption. As a result, ionic air pumping has been applied in airflow control applications [15], cooling applications [16], propulsion technology [17], micro-pump design [11], gas spectrometry [18], noise control [19], precipitation filtering [20–22], bio-electronic device [23–25], synthetic jet [26]. Integration of EHD force to ionic pumping has also been used for spectrometry [27], vibrating element [28] or aerosol sampling [29,30].

Many authors have reported the characteristics of various electrode arrangements, which are typically point-to-plane [31], point-to-grid [32], point-to-ring [33] or wire-to-plate [34]. Other modifications, including wire-to-inclined wing [16], parallel plates [35], wire-to-rod [36], rod-to-plate [37], point-to-parallel plate [38], wire-to-cylinder [39], sphere-to-sphere [37], wire-to-wire [40], point-to-wire [32], point-to-cylinder [41], and conical electrode [42] have been recently suggested. The fundamental requirements of the above systems are a high-curvature electrode that generates ions and a low-curvature reference electrode, which is placed downstream to define the movement of the charged particles. Ion wind is generated at high-curvature locations, yielding high velocity near the surface of the reference electrode. The citations above provide great references in the field although actual designs of a ready-to-use device were not always provided.

Depending on the prospective application, one may find that charge from ionic wind needs to be neutralized or controllably minimized. Owing to the charge, ion wind on one hand brings unique applications in flow directed to targets, but on the other hand raises significant challenges in designing a millimetre-scale device because the charge tends to attach to the wall, therefore most of the works for ionic air pumping are with rather large systems where a far-field boundary condition is applied [43]. Although in some cases the accumulated space charge was used as the sensing source for very low velocimetry [23], in general the discharge ion current and the space charge need to be compensated for by electrons in the downstream space to prevent charging of the device [44,45]. Other problems also exist, such as the application in inertial sensing, where the flow must be able to freely vibrate in three dimensional space under inertial force, which is however dominated by electrostatic force in limited space [46–49]. In bio-applications, the aerosol particles with highly reactive ionization products are destructive for living cells, spore or viruses [50,51], therefore neutralization with gaseous counter-ions or corona neutralizer is also attractive for the formation of zero-charged aerosol [52]. One of the proposals has been the mixing of positively and negatively charged particles produced by electrohydrodynamics atomization from several independent spray sources [53,54]. Another application of neutralized, or mildly neutralized, ion wind is for electrospun polymer nanofiber to overcome the intrinsic instability of the process [55].

In this paper, we present an ion wind pumping device with a unique bipolar discharge configuration using electrodes arranged symmetrically from a single power source, thus minimizing the footprint. The experiment and simulation show that with such a symmetrical configuration, the air movement can be optimized to be parallel to the axes of the electrodes, and directed away from the device. It is well-known that ion wind can adjust its flow rate by alternating the discharging voltage/current with utilizing an external flow meter as a calibration tool, thus we propose a feasible approach by integrating a “ready-used” calibrating element into device as a hotwire anemometer, which has been widely used in inertial fluidic sensors [56,57]. With both charges simultaneously released from a power source, the amount of net charge released out of the device is small and in principle can be controlled in various ways, for example by alternating the mixing condition [52]. Owing to the easy scalability of the configuration and the low net charge, the proposed system is beneficial for applications with space constraints [58], and for applications where a neutralized ion wind is required, such as fluidic amplifiers, fluidic oscillators or fluidic actuators [59–61]. This gives the device a hybrid application of micro pump for outer space use and micro discharge for internal use. This study is also promising for vortex or convective inertial devices [62,63], particle separation and extraction into portable microfluidic labs-on-a-chip [64]. Other prospective views of this configuration are towards the microfluidics-to-mass spectrometry to provide coupling, mixing methods between microfluidic devices and mass spectrometers [65–67], pharmaceutical inhalation aerosol by bipolarly charged particles [68] or to generate mildly charged particles for insecticide dispensing where one electrode sprays the formulation of interest [69].

In the remaining part of the paper, the design and working principle of the device are described, followed by experimental and numerical setup. The air flow is validated by the integrated thermal sensing elements (hotwires) implemented at several positions along the downstream channel. The simulation is conducted in an open-source code environment, OpenFOAM. The device itself is easy-to-build and can be implemented cost effectively because of its simple and commercially available components.

2. Working principle

An ion wind generator can be realized with various designs, a typical needle-to-ring configuration consisting of a corona electrode as a pin and a collector electrode as a ring is shown in Fig. 1a. Ion wind is generated at the pin and yields high velocity near the surface of the counter electrodes, where the charge is neutralized. In our configuration, two electrodes of opposite polarity are placed in parallel, and generate charged particles from a single power source (Fig. 1b). 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 as explained below. In our design, both electrodes serve as emitters, and also represent the reference electrode defining the electric field.