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Performance of an electrohydrodynamic gas pump fitted within a nozzle

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A B S T R A C T

In this study, an EHD gas pump fitted within a conical nozzle is examined for three diameter ratios (DR = 1/2, 1/3, and 1/4). It has been tested for an applied voltage ranging from corona threshold up to sparkover. The results are critically examined to reveal the velocity profile of the corona jet at the downstream of the pump exit as well as the relation between the pump performance and diameter ratio. It has been found that three nozzle configurations have their own characteristics and performs differently under various conditions. A pump with a diameter ratio of 1/2 performs the best in maintaining a velocity profile that can extend the longest distance downstream of the pump while a pump with a diameter ratio of 1/4 can produce the highest velocity with the smallest increase in corona current. The maximum performance of 3 L/min/W is achieved by the pump with a diameter ratio of 1/2 operating at 15 kV. It is found that the flow and electric characteristic are not linearly dependent on the diameter ratio of the nozzle. As such, the design of an EHD nozzle gas pump for a specific application needs to consider an optimal combination of these parameters.

1. Introduction

Corona discharge is a low temperature plasma. The onset of corona discharge requires two electrodes with different curvature. By applying a high voltage (usually in the kV range) to pin-like or wire-like emitting electrode, the electric field near the tip of electrode is intensified. When the electric field strength is greater than the dielectric strength of air, air molecules close to the electrode tip break down and become ionized. Driven by Coulomb force, ions migrate to the grounded electrode. During the migration, the momentum of ions is transferred to neutral molecules through collision, which produces additional ions pairs and leads to the generation of corona wind. The drifted ions are collected by the grounded plate and output an electric current (in the μA to mA range).

In recent years, miniaturization of electronic components has been realized due to the advancement in technology. However, this has also led to a tremendous increase in the heat flux it generates. The traditional heat removal techniques, such as forced convection by fan or natural convection through fins, are no longer sufficient. A breakthrough in the heat transfer enhancement technique becomes highly desirable. Electrohydrodynamics (EHD) is one of the promising technologies in removing heat from a targeted area [1,2]. It utilizes the ionic wind generated from corona discharge to perturb the momentum and thermal boundary layers over a heated surface [3]. In addition to the application in heat transfer enhancement, EHD technique has been widely applied to other fields [4]. For example, it has been employed in electrostatic precipitators (ESPs) for the control of particle emission in power industry as well as cement plants. Since corona discharge produces low temperature plasma, it can be used for food dehydration [5–7] to keep the nutrients from thermal degradation due to high temperature. A plasma actuator embedded on an airfoil can also be used for flow control to put off the flow separation point that leads to drag reduction [8–11].

Another important application of EHD technique is gas pumping. An EHD gas pump has no moving component, thus no noise induced by vibration. In addition, its operation can be easily controlled by varying the electric field. While the applied voltage may be high, the current involved is usually small, which makes the power consumption considerably insignificant. This has become one of the most attractive features for EHD technique. In recent years, there has been a surge of interest in the application of EHD technique for pumping dielectric liquids [12]. Because of their low power consumption and no moving part, EHD pumps have been considered a valuable alternative for conventional pumps.

A variety of EHD gas pumps have been studied in recent years, the electrode configurations considered in these studies include pin-plate [13], wire-rod [14,15], wire-plate [16–20], and needle-mesh [21]. Among these studies, Zhao and Adamiak [13] examined the flow field produced by a corona wind generator with pin-plate configuration. Their results shows that the wind velocity increases to a highest value

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near emitting electrode, and decreases radially away from electrode. Their results also show that recirculation occurs due to EHD jet flow. Komeili et al. [15] investigated the flow induced by an EHD gas pump with wire-rod geometry. They reported that for the same pipe diameter and electrode spacing, the induced air velocity increased with the rod diameter. However, in the consideration of power consumption, they suggested using a rod electrode with a smaller diameter to produce a specified flow rate. Tsubone et al. [17] studied the characteristics of flows produced by an EHD gas pump with wire-plate configuration. Because of the similarity between an EHD flow and a jet flow, they observed the presence of turbulent eddies and small scale recirculation at low Reynolds numbers. Chang et al. [18] studied the effect of the position of emitting electrode on the resulting flow direction. They used wire as the emitting electrode and non-parallel plates as the grounded electrode. Their results showed that the flow direction could be modified when the location of the emitting electrode was changed along the pipe centerline. In other words, the flow direction can be manipulated by changing the position of electrodes.

Tsubone et al. [19] studied the flows produced by an EHD gas pump with wire and non-parallel plate configuration in a converging cone. They also explored the use of a two-stage EHD gas pump. Their result shows no obvious change in pressure at the upstream of emitting electrode but it increases at the downstream of emitting electrode. In the study of two-stage EHD gas pump, they reported that corona wind velocity and volume flow rate could be enhanced by 15%. Chang et al. [20] studied the electric discharge and flow characteristics of an EHD gas pump with the same electrode configuration as that used in Ref. [19]. However, their emphasis was on placed on the effect of converging angle formed by the plates. An increase in the air velocity and pressure was reported when the channel converging angle was 3°. When the angle became greater than 3°, recirculating flow was observed inside the channel. As a result, the exit air velocity and pressure were not significantly increased. They attributed that to a greater flow resistance caused by the increased converging angle (i.e., a smaller exit area). Their result also shows that near emitting electrode, pressure gradient and turbulent intensity are the highest. The possible reason is that the resistance caused by the formation of recirculation flow at certain operated condition.

Rickard et al. [22] studied the flow produced by an EHD gas pump with and without a nozzle attached at the exit of the pump. Their results showed that only a slight increase in velocity could be achieved by adding a converging nozzle downstream of the electrodes. It is worthwhile to mention that velocity profiles were measured by hotwire anemometry and particle image velocimetry (PIV) in their study. They noted that seed-based measurement techniques (such as PIV) were complicated by the charging of seed particles. As seed particles entrained through the region of corona discharge, they acquired electric charges causing them to deviate from the flow streamlines under the influence of Coulomb force.

Recently Brindle and Lai [23] have also studied the characteristics of the corona jets produced from an EHD gas pump with a nozzle attached at the exit of the pump. Although the electrode configuration of their pump was different from that of Rickard et al. [22], their findings were nevertheless consistent with those reported by the latter.

The flow characteristics of a single stage cylindrical EHD gas pump with four emitting electrodes was studied by Brown and Lai [24]. They examined two pumps of different diameter for various electrode spacing. They noted that operating an EHD pump at a higher applied voltage does not necessarily improve its performance, but rather it would simply increase its power consumption. Most importantly, they noticed that the volume flow rate appeared to approach an asymptotic value as the applied voltage increased. Recently, Birhane et al. [25] extended the study of Brown and Lai [24] to examine the flow characteristics of an EHD pump with eight emitting electrodes. They confirmed the previous finding [24] that there exists a maximum volume flow rate that a single-stage EHD pump can deliver before the occurrence of sparkover. Zhang and Lai [26] have concluded and pointed out that higher applied voltage does not necessarily enhance the efficiency of gas pump, instead, resulting in more power consumption.

It is clear from the literature review above that ultimately one may need to use a multi-stage EHD gas pump to increase or even sustain the volume flow rate of its induced flow. However, a multi-stage pump usually takes up more space. For applications where space is a factor of constraint and a single-stage pump is the only choice available, then an alternative electrode configuration would be required to improve its performance. To this end, previous studies have considered non-parallel plate [17–20] or nozzle [22,23] with varying degree of success. Clearly, more studies are required to fully understand the electrical discharge and flow characteristics in an EHD gas pump using alternative electrode configurations. The motivation of this study is to examine the performance of a single-stage EHD gas pump using new alternative electric configuration. Different from those of the previous studies, the present EHD gas pump is entirely fitted into a nozzle for its compactness (as a great contrast to that of [23]). For comparison, the main dimensions of the pump are kept the same as those used by Birhane et al. [25].

2. Experiment setup and procedure

The schematic of the experimental setup used in this study is shown in Fig. 1. The EHD gas pump has a shape of a nozzle and is fabricated by 3D printing using Acrylonitrile Butadiene Styrene (ABS) thermoplastic resin as the material (Fig. 2). The length of the EHD pump is fixed at 126 mm. While the inner diameter of the inlet is fixed at 61.8 mm, three sizes of the outlet have been considered so that the resulting nozzle has a diameter ratio of 1/2, 1/3, and 1/4, which corresponds to a converging angle of 7°, 9° and 10°, respectively. Both the inlet diameter and length of the EHD pumps are the same as those employed by Birhane et al. [25]. Since the EHD gas pump studied by Birhance et al. [25] has a constant diameter throughout, it can be considered as a special case of the present study with the diameter ratio of unity. In addition, the electrode configuration is the same as that used by Birhane et al. [25]. A copper ring which serves as a common bus for emitting electrodes is

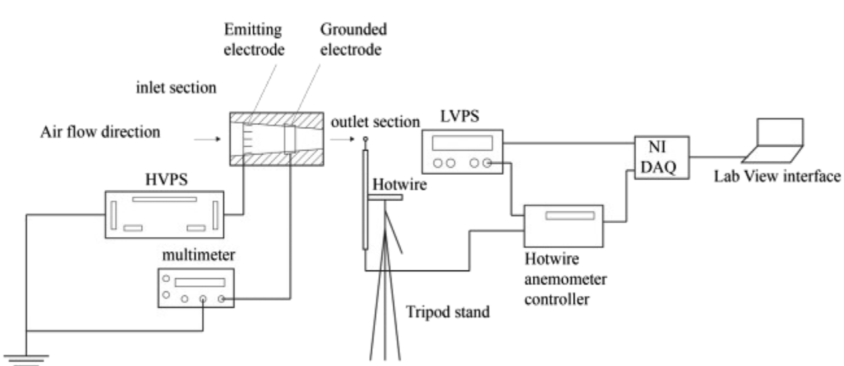

Fig. 1. Schematic of experimental setup.