Performance of an Electrohydrodynamic Gas Pump Fitted in a Nozzle

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***Abstract*— 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.**

I. 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 becomes 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 process [5-7] to keep the nutrients from thermal degradation due to high temperature. A plasma actuator embedded on 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 near emitting electrode, and decreases radially away from electrode. Their results also show that recirculation occrurs 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 [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 degrees. When the angle became greater than 3 degrees, 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. Zhang and Lai conclude and point out that higher applied voltage does not necessarily enhance the efficiency of gas pump, instead, resulting in more power consumption. 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.

The flow characteristics of a single stage cylindrical EHD gas pump with four emitting electrodes was studied by Brown and Lai [23]. 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. [24] extended the study of Brown and Lai [23] to examine the flow characteristics of an EHD pump with eight emitting electrodes. They confirmed the previous finding [23] that there exists a maximum volume flow rate that a single-stage EHD pump can deliver before the occurrence of sparkover. As such, one may have to resort to a multi-stage EHD pump than simply increasing the applied voltage of a single stage pump for a better use of energy.

It is clear from the literature review above that ultimately one need to use a multi-stage EHD gas pump to increase or even sustain the volume flow rate of its induced flow. However, if a single-stage EHD gas pump were 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] 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. For comparison, the main dimensions of the pump are kept the same as those used by Birhane et al. [24].

II. EXPERIMENTAL 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. [24]. Since the EHD gas pump studied by Birhance et al. [24] 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

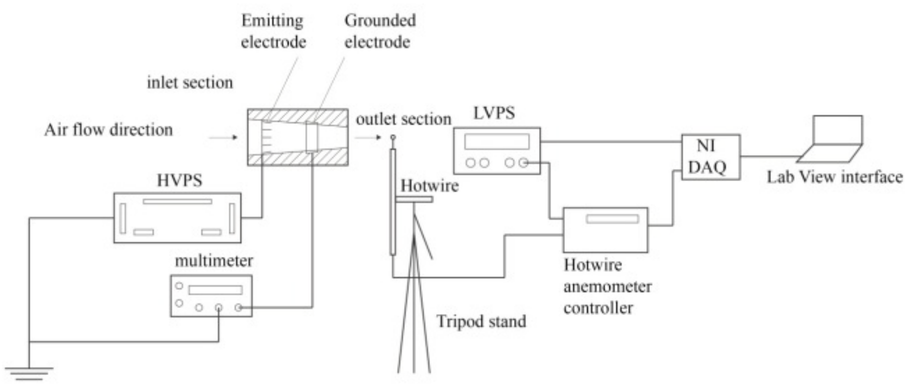
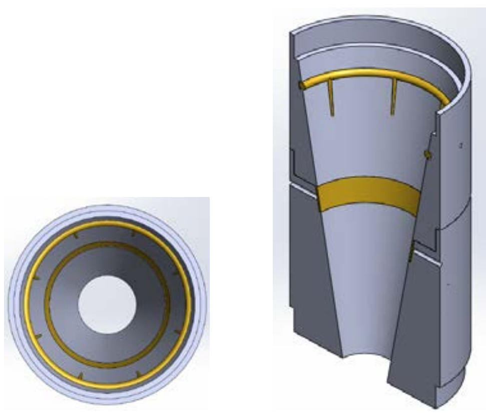


Fig. 1 Schematic of experimental setup.



(a) (b)

Fig. 2 An EHD gas pump with a diameter ratio of 1/3, (a) top view, (b) cross-sectional view.

the same as that used by Birhane et al. [24]. The emitting electrodes consist of eight angularly even-spaced pins with each pin of 0.4 mm in diameter and 15 mm long. Since the EHD pump is fitted in a nozzle, it should be noted that the spacing between the tips of two neighboring emitting electrodes is actually getting smaller as the diameter ratio reduces. The corresponding grounded electrode is a flat plate with a thickness of 0.5 mm and a width of 10 mm and is placed downstream to the emitting electrodes. Because of the shape of the nozzle, the grounded plate is also molded to the cone shape. Both electrodes are made of copper and are flush mounted on the inner wall of the nozzle. Th use of flush mounted electrodes in this study is considered to have several advantages over those used in the previous studies. These include the ease of maintenance, reducing flow obstruction, and effective disruption of boundary layer growth. The spacing between the emitting and grounded electrodes is fixed at 25 mm. To generate corona wind, a high voltage power supply (manufactured by You-Shang Technical Corp. in Taiwan) is connected to the emitting electrodes through a base ring. A multimeter (FLUKE 287) is used to measure the corona current on the grounded plate of the EHD gas pump. It has an accuracy of ± 1V in voltage and 2% in current. Although corona discharge with negative polarity can produce higher velocity, it is inherently more unstable and has a higher ozone generation rate. Thus, only the positive corona discharge is used in this study. A hot-wire anemometer (TSI 8475) is used for the measurement of the corona wind velocity. The hotwire anemometer has an accuracy of ± 0.05% of the full scale with minimum resolution of 0.07 m/s. The sensitivity of the anemometer is 0.07% of the full scale which translates to 0.035 m/s. The acquired signal is transferred to a data acquisition system by National Instrument (NI) and is converted to velocity by LabView program. Since air temperature and humidity can significantly affect corona discharge, a chamber with an air-conditioner and a dehumidifier, which functions like an environmental chamber, is used to house the experimental setup. By closely monitoring the humidity and temperature, both values were maintained within 55~62%, and 20~23 °C, respectively.

For the present study, the nozzle inlet diameter (D) which is fixed at 61.8 mm has been used as the characteristic length. To study the flow characteristics of the corona wind thus produced, velocities are measured at four sections downstream of the nozzle exit (1D, 2D, 3D and 4D). At each section, velocities are measured radially outward from the centerline of the nozzle at an increment of 3 mm. It has been observed that the corona jet produced is nearly axi-symmetrical. With an increase in the axial distance from the nozzle exit, the jet width increases. As such, the number of the sampling points is also increased proportionally to get a detailed profile of the corona jet. The data is recorded 20 times at each sampling point to acquire a statistical average. The uncertainty associated with the measurements was calculated by the method proposed by Steele et al. [25]. The velocity measured by the hotwire anemometer had an uncertainty of 0.027 m/s while the average current collected on the ground electrode has an uncertainty of 0.07 μA.

III. RESULTS AND DISCUSSION

For the present study, the onset of corona discharge is observed to be at a voltage slightly less than 14 kV and it breaks down near a voltage around 18 kV. For safety, experiments have been conducted in the voltage range between 14 kV and 17 kV. The

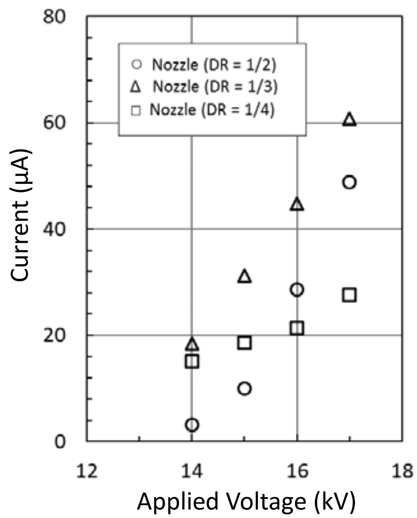


Fig. 3 Voltage-current characteristic curves of the EHD gas pumps.

voltage-current relations observed from the present study are shown in Fig. 3. The applicable range for the present EHD pumps is considerably smaller than that of the EHD pump in a circular tube [24], which has an onset voltage at 17 kV. Although the total length, inlet diameter, and the spacing between the emitting and grounded electrodes for the EHD pumps used in both studies are the same, the distance between the two neighboring emitting electrodes in the present study becomes smaller as the diameter ratio of the nozzle decreases. As such, the onset of corona discharge for the present EHD pumps takes place at a smaller applied voltage and produces a smaller current. Correspondingly, the sparkover voltage is also reduced. For all cases, corona current increases with the applied voltage. For nozzles with a diameter ratio of 1/2 and 1/3, the trend is similar to that of a circular tube and follows a power-law function. Corona current is observed to increase at a much faster rate for the nozzle with a diameter ratio of 1/3. If the diameter ratio is further reduced to 1/4, the increase in corona current with the applied voltage becomes less significant, which seems to suggest the existence of a possible “saturated” state where corona current becomes less dependent on the applied voltage. The present result clearly shows that installing an EHD pump in a nozzle can effectively reduce the corona onset voltage and minimize the power required.

For the present EHD pump, the corona wind generated is channeling through a converging nozzle, producing a strong jet issuing from the nozzle exit. The maximum flow velocity is expected to be at the centerline of the nozzle. As the jet travels downstream, its width spreads and its maximum velocity reduces. The centerline velocities of the corona jets produced at various applied voltages are shown in Fig. 4. As observed, for a given nozzle, the centerline velocity increases with the applied voltage, but its magnitude decreases as the jet travels downstream. Also observed, the centerline velocity increases with a reduction in the nozzle diameter ratio (i.e., a larger contraction in the cross-sectional area) for a given applied voltage. It is further observed that a nozzle with a

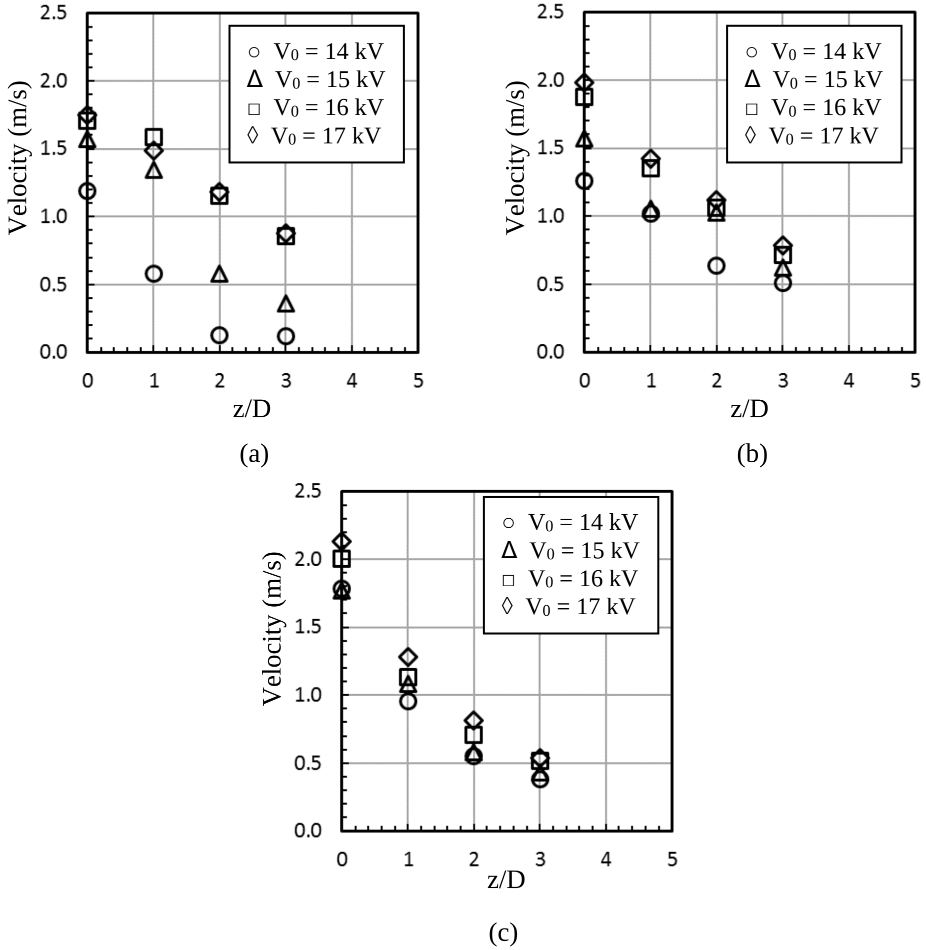


Fig. 4 Variation of the centerline velocity at various downstream distances from the nozzle exit, (a) DR = 1/2, (b) DR = 1/3, and (c) DR = 1/4.

smaller diameter ratio experiences a steeper reduction in the centerline velocity as the jet moves downstream. This seems to suggest that, the corona jet produced by a nozzle with a smaller diameter ratio, while having a higher centerline velocity, it does not travel far. For example, one observes that, at z/D = 3, the centerline velocity of a jet produced by a nozzle with a diameter ratio of 1/4 has a centerline velocity which is nearly one half ofthat produced by a nozzle with a diameter ratio of 1/2 at a higher applied voltage. Apparently, the flow restructuring inside the nozzle has consumed a considerable amount of energy. The present result is consistent with those reported by Chang et al. [20]. Although the previous study was conducted using non-parallel plates, which can be thought as a planar nozzle, they observed that when the converging angle is greater than 3 degrees, recirculating flow was formed inside the channel which led to a greater flow re-

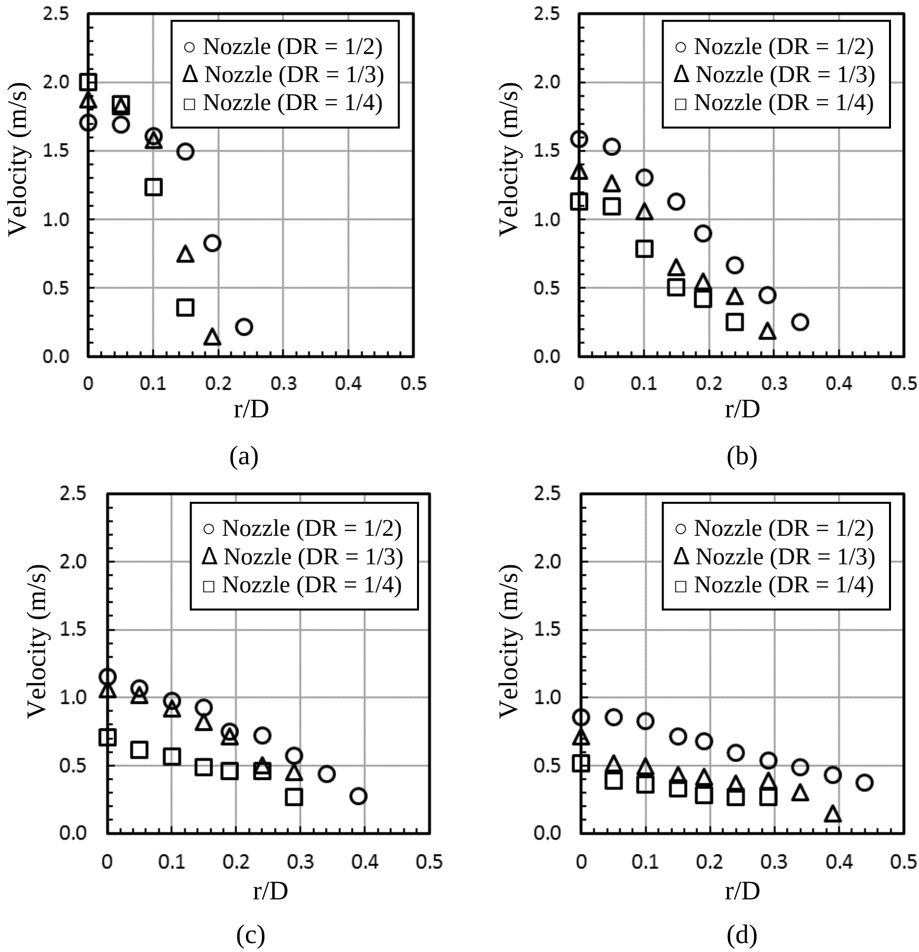


Fig. 5 Velocity profiles of the corona jet at various downstream distances from the nozzle exit (V_0 = 16 kV), (a) z/D = 0, (b) z/D = 1, (c) z/D = 2, and (d) z/D = 3.

sistance. Also, it is worthy to point out that Rickard, et al. [22] studied the flow produced by an EHD gas pump with a nozzle attached at the exit of the pump. Their results showed that the air velocity was limited to 2.4 m/s regardless of the exit-to-inlet area ratio (i.e., the diameter ratio of the nozzle). The present results may first seem contra-dicttory to theirs. However, a closer look at their experimental setup, one notices that the velocity measurement in their study was not performed in-situ, but rather at a distance further downstream of the nozzle exit. The jet produced by their EHD gas pump was directed to the sampling site using a rubber tubing. Clearly the pressure restriction caused by the tubing has compromised their results.

The velocity profiles of the corona jet produced at the applied voltage of 16 kV are shown in Fig. 5 for various cross-sections downstream from the nozzle exit. From the

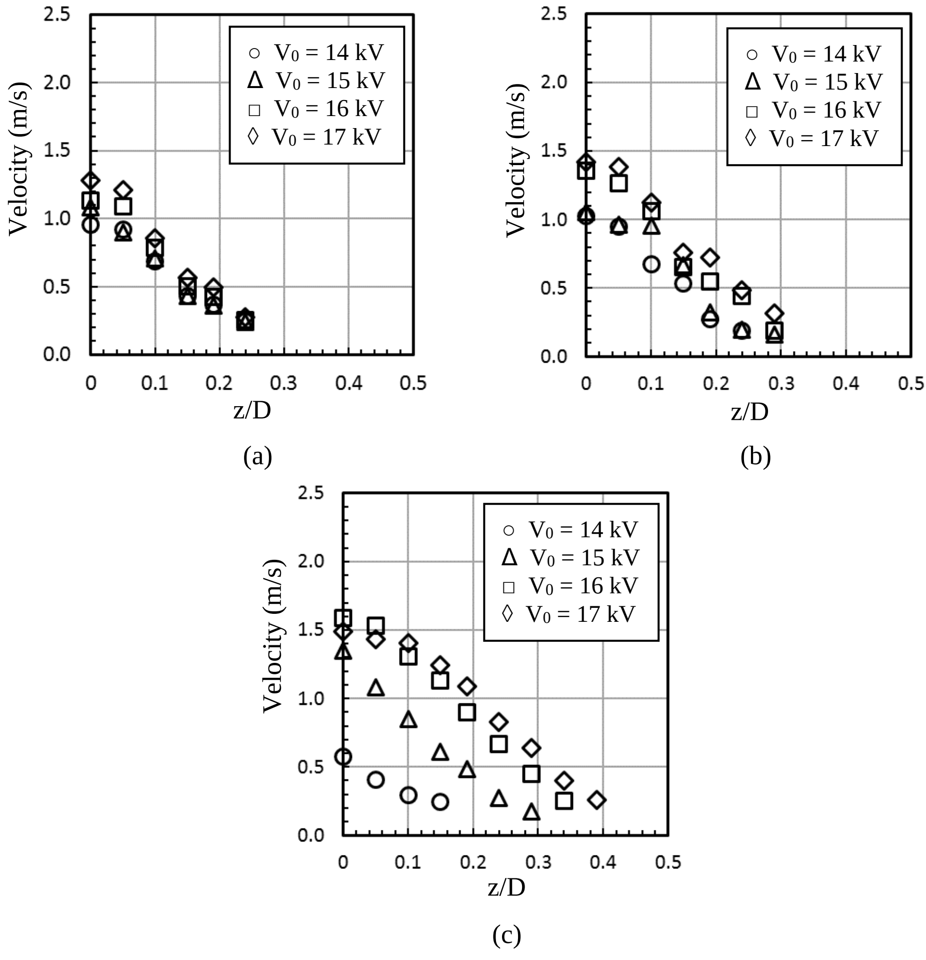


Fig. 6 Velocity profiles of the corona jet produced by nozzles with various diameter ratios (at z/D = 2 from the nozzle exit), (a) DR = 1/4, (b) DR = 1/3, and (c) DR = 1/2.

figures shown, one observes that the width of the corona jet is the smallest while its velocity is the largest at the nozzle exit (Fig. 5(a)). The nozzle with the smallest diameter ratio (i.e., the largest contraction in the cross-sectional area) produces the highest velocity at the centerline and has the smallest jet width. As the jet travels further downstream,one observes that the jet width increase but the velocity reduces (Fig. 5(b), 5(c) and 5(d)). However, one notices that the nozzle with the smallest diameter ratio (DR = 1/4), while having the highest velocity at the nozzle exit, dissipates its momentum faster than the other two and has the lowest velocity downstream. On the other hand, the nozzle with the largest diameter ratio not only has the highest velocity, but also the largest jet width. It produces a corona jet that can reach further and wider. This can be explained as follows. Since the electrodes are flush mounted on the wall, the corona wind produced by the EHD pump is similar to a wall jet and has the highest velocity near the wall. In a circular tube (which corresponds to a nozzle with DR = 1), the resulting velocity profile has a hump from each side of the wall and is nearly flat at the core region [24]. As the jet moves downstream, its momentum diffuses radially toward the center. If the passage is long enough, the flow will eventually become fully developed and attain a parabolic profile. Apparently, with a contraction in the cross-sectional area, the flow has to restructure itself before exiting the nozzle. Since the length of the nozzle is fixed, the flow field inside a nozzle with a smaller diameter ratio (i.e., a larger contraction in the cross-sectional area) experiences a more significant restructuring process.

The velocity profile of a corona jet produced by a nozzle can also be examined from Fig. 6 where it is displayed at the distance of z/D = 2 downstream from the nozzle exit for various diameter ratios. In general, one observes that the jet velocity increases as the applied voltage increases. As the nozzle is further contracted (i.e., the diameter ratio decreases), the jet width reduces and the velocity profiles become less separable. For example, for the nozzle with DR = 1/4 (Fig. 6(a)), one observes that its jet width is smaller than those of the other two. As the applied voltage increases, only the velocity at the core region increases while the jet width and the peripheral velocity profile are less affected. As the diameter ratio increases (i.e., less contraction in the nozzle), not only the jet width increases with the applied voltage, but also the velocity profile becomes more visibly different (Fig. 6(c)). Although a nozzle with a smaller diameter ratio (i.e., a larger contraction) produces a higher velocity at the centerline, it is at the expense of a reduced flow rate. A significant amount of energy is dissipated through internal friction due to the flow restructuring.

The volume flow rate produced by the three EHD gas pumps examined is shown in Fig. 7. The volume flow rate reported from the previous study [24] is also included for comparison. As observed, all volume flow rates increase with the applied voltage, but

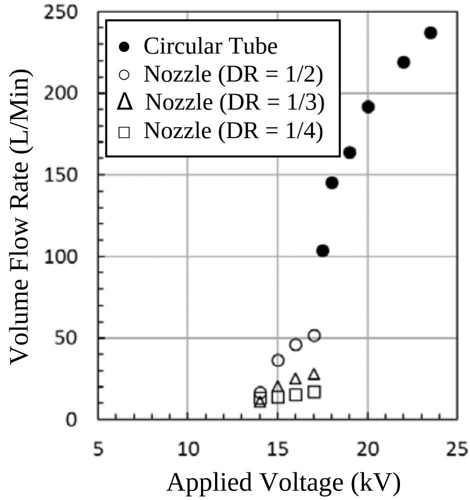


Fig. 7 Volume flow rate produced by the three EHD gas pumps examined.

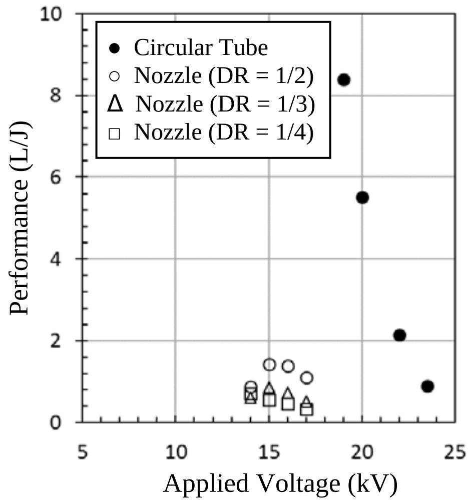


Fig. 8 Performance of the three EHD gas pumps examined.

they are significantly smaller than that produced by an EHD gas pump in a circular tube with the same inlet diameter [24]. Also observed is that the volume flow rate first increases as the diameter ratio reduces from 1/2 to 1/3. However, a further reduction in the diameter ratio does not lead to an increase in the volume flow rate. Instead, its volumeflow rate falls between those of the diameter ratio of 1/2 and 1/3 when the applied voltage is less than 16 kV, and becomes the smallest when the applied voltage is further increased. This trend has also been reported from the previous study by Rickard, et al. [22]. As discussed earlier, flow restructuring takes place when the diameter ratio of the nozzle decreases. Frictional loss due to flow restructuring becomes more significant for nozzles with a smaller diameter ratio at a higher applied voltage. Although the nozzle with the smallest diameter ratio produces the maximum axial velocity at the centerline, it has the smallest cross-sectional area at the outlet. As a result, its volume flow rate may not be greater than those of the other two.

To evaluate the performance of an EHD gas pump, the following criterion is used.

$$\text{perforamce} = \frac{\text{volume flow rate}}{\text{power input}}, \tag{1}$$

which is the fluid volume delivered by a unit input of energy. This parameter addresses how efficiently energy is utilized. The performance of three EHD gas pump examined is shown in Fig. 8. For the nozzles with the diameter ratio of 1/2 and 1/3, they first show an increasing trend between 14 kV and 15 kV, then decrease at 16 kV and 17 kV. But for the nozzle with the largest contraction in the cross-sectional area (i.e., the one with the diameter ratio of 1/4D), it has the best performance at 14 kV, then its performance decreases as the applied voltage increases. Clearly, much of its input energy is wasted in the flow restructuring process.

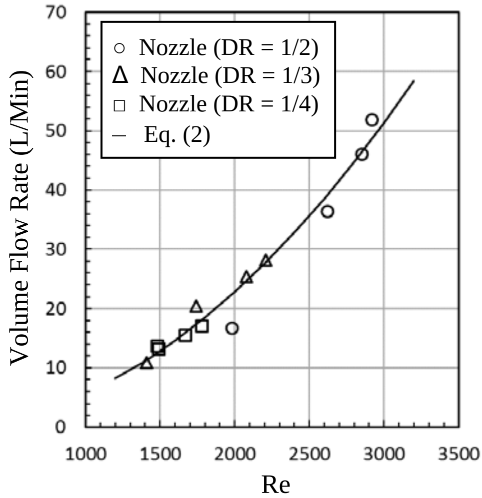


Fig. 9 Volume flow rate as a function of Reynolds number.

The volume flow rates delivered by the EHD gas pumps considered can be best correlated as a function of Reynolds number as shown in Fig. 9. The correlation is given below

$$Q = (5.702\ E\text{-}6)\ Re^2, \qquad (2)$$

where Q is the volume flow rate in L/min and Re (= $u_{max}D_o/\nu$) is the Reynolds number. For the present study, the Reynolds number is based on the centerline air velocity (i.e., the maximum velocity u_{max}) at the nozzle exit and the outlet diameter D_o. Since the nozzle exit velocity is a function of both applied voltage and diameter ratio, so is the Reynolds number thus defined. The correlation coefficient is 0.968 for the proposed function, which is an indication of an excellent fit statistically. This correlation is applicable for an applied voltage from the onset of corona up to sparkover. It also holds true for two limiting cases. The first is when the applied voltage is below the corona onset voltage, there is no flow (Re = 0 and thus Q = 0). The other limiting case is when the diameter ratio approaches zero (and hence the Reynolds number), which leads to no flow as well. The latter trend is also observed by Rickard, et al. [22].

IV. CONCLUSION

Experiments have been conducted to study the characteristics of flow produced by an EHD gas pump fitted in a nozzle. The results show that the performance of the pump is complicated by the applied voltage and diameter ratio of the nozzle. For all nozzles considered, the corona current increases with the applied voltage. When compared with the EHD gas pump in a circular tube with the same inlet diameter, the spacing between two neighboring emitting tips for the present case is closer and the resulting electric field is more uniform. Consequently, the corona current, onset voltage, and applicable range of applied voltage are all lower than those of an EHD gas pump in a circular tube. In other words, the power consumption is lower. However, the rate of increase in the corona current with the applied voltage is the smallest for the nozzle with the diameter ratio of 1/4. As the diameter ratio reduces, the spacing between two neighboring tips becomes closer and the electric field that it creates also becomes more uniform, and thus leads to a more moderate increase in the slope of the voltage-current curve. The results also show that an EHD gas pump fitted in a nozzle can effectively create a concentrate air jet with a higher velocity than that produced by an EHD gas pump in a circular tube. The maximum air velocity it produced increases with a reduction in the diameter ratio of the nozzle. However, this has been attained at the expense of the volume flow rate it generated. In addition, a nozzle with a smaller diameter ratio experiences a higher flow resistance, and hence leads to a shorter jet penetration depth. Perhaps the most important contribution of the present study is the correlation proposed in Eq. (2), where the volume flow rate produced by an EHD gap pump fitted in a nozzle is superbly correlated with the Reynolds number. Since the Reynolds number is based on the maximum velocity at the nozzle exit, it adequately represents the applied voltage and the diameter ratio involved.

In summary, the major advantage of an EHD gas pump fitted in a nozzle is not the volume flow rate it delivers, instead, it is the maximum velocity and the penetration depth of the corona jet that it creates with a lower power consumption. It can be best used in applications where a higher jet velocity and a lower power consumption are required. In addition, it can be customized with the aid of the correlation proposed to get the desired results under various applied voltages.

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