**Particle Dynamics in Corona Induced Electro-hydrodynamic Flow**

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**ABSTRACT**

Particle behavior in electro-hydrodynamic (EHD) flow induced by corona discharge is investigated. EHD flow in a point-to-tube corona configuration is studied experimentally and numerically. Multiphysics numerical model couples ion transport equation and the Navier-Stokes equations (NSE) to solve for the spatiotemporal distribution of electric field, charge density, and flow field; the results are compared with experimental velocity profiles at the exit. The velocity and the flow rate increase with corona voltage, the maximum velocity of EHD flow is located at the axis and ranges from ~1-4 m/s. Collection efficiency trends for 20-150 nm nanoparticle on the ground electrode for ambient and NaCl particles are in good agreement with the theoretical models. However, for particles in 10-20 nm size range, the measured collection efficiency increases for smaller particles due to increase particle charging efficiency in the high-intensity electric field and high charge density environment of the EHD driven flow. These conditions allow a greater number of particles below 20 nm to acquire and hold a single charge, for particles approaching 20 nm the collection efficiency reduces due to their increase in mass, thus lower electrical mobility. For particles larger than 20 nm, the electrical mobility and the collection increases as they acquire multiple charges on a single particle.

Keywords: electro-hydrodynamics; corona discharge; electrostatic collector; ionic wind; ultrafine PM; particle charging; numerical modeling; electrostatic precipitator

**I. INTRODUCTION**

Electrostatic precipitation (ESP) is a technique where an electro-hydrodynamic particle motion occurs to separate the particles from gases [1-4]. With the development of the sophisticated nanoparticle synthesis [5,6], size fraction particulates from various sources and locations [7-9], electrostatic precipitation can be used to collect nanoparticles from an aerosol. The advantage of electrostatic precipitation is that electrostatic force on a charged particle under the influence of external electric field can be greater than gravitational, inertial and thermal forces. Many researchers have developed electrostatic precipitator-based devices for the collection of fine and ultrafine particles. Most conventional ESPs feature either a point-plate, point-cylinder, wire-plate, point-ring configuration. Devices with point-plate configuration have reported in the mid-20th century [10] and have been used in the design of particle collectors [11]. Miller et al. developed a miniature single stage point to plate electrostatic based device; they collected 30 nm to 400 nm NaCl particles at 0.055 slpm, flow rate and 6.8 kV corona voltage [12] with a collection efficiency of ~86%. Attempts have been made to determine the size wise collection efficiency on axisymmetric designs [13-17]. Dixens and Fissan designed a two-stage device to collect 0.3 μm to 10 μm particles [13]. The results showed that the collection efficiency was up to 100% at 0.3 slpm flow rate and 25 kV corona voltage. Models have been developed to estimate the size-dependent collection efficiencies in the point-plane configuration using axisymmetric designs that incorporated separate charging and collection regions [13,18]. A point-to-tube electrostatic sampler has

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been demonstrated to collect nanoparticles and collection efficiency of the device (approaching 98%) has been evaluated for both positive and negative corona [17]. Han et al. have designed a handheld wire-wire device and reported collection of 26 nm to 310 nm polystyrene particles; the study has also been extended to biological samples. In a typical ESP collector, the flow is induced by an external source if the corona discharge induced flow is present it is considered as a secondary flow is often ignored [19,20]. However, the electrostatic force used to collect particles can be used to generate the flow.

Corona discharge is an electrical breakdown of air in which ions are generated in the high electric field region near the high energy anode; these ions drift towards the grounded cathode. The ions collide with the neutral air molecules results in a macroscopic wind, which is also known as electro-hydrodynamic (EHD) flow or ionic wind. Among other applications, the EHD effect has been used for plasma-assisted combustion [21,22], convective cooling [23-26] and control of the aircraft [27,28]. The success of EHD technology has been limited due to the modest pressure achieved by the EHD blowers; however, in the applications with the low pressure drop, the EHD driven flow may be appropriate. Several benefits of the EHD approach are the ability to operate at a small scale; no moving parts are required to produce the flow, straightforward control of the system, and quiet operation. The corona induced EHD flow converts electric energy into kinetic energy directly and breaks the size limit of any moving mechanical parts. Such an ESP device has a very short response time and optimal for real-time control. The current to voltage relationship describes the system behavior related to ion transport between the electrodes. The classical voltage to the current relationship is derived by Townsend for a coaxial corona configuration [29]. This quadratic relationship has been observed for other configurations, i.e., point to plate [30] and point to ring corona [31]. A generalized analytical model for voltage to current and voltage to velocity relationship for EHD driven flow has been recently proposed [32]. The maximum velocity for point-to-ring electrode configuration was recorded at ~9 m/s; the analytical model has a good comparison with the experimental data at the center (EHD dominated flow), and it decreases near the walls of the internal flow channel (viscosity dominated region). To gain insight into the complex EHD flow multiphysics modeling is required; the properties of the electric field, ion concentration, and velocity fields can be computed using numerical methods. The ion interaction with the neutral air molecules can be modeled as an external force term in the NSE. Most EHD flow models [33-36] used an iterative method to solve for the electric field and electric force. The models iteratively set a constant space charge on the anode so that the cathode current matches the experimental results. This method is inefficient and requires multiple iterations. In [31] the authors solve the modified NSE numerically. There a volumetric flux charge density is introduced as a source term in a finite volume solver, the flux boundary conditions are determined based on the experimentally measured cathode current. The ionization boundary has been defined by Peek’s law [37], these thresholds for the onset of the ionization are imposed in numerical ionization zone. In the EHD flow analysis, a non-dimensional parameter X (ratio of the electrostatic over the inertial terms) defines the regions where the EHD effect dominates the inertial terms of the NSE. The analysis of EHD flow in the point-to-ring corona [31] shows the large region with EHD dominated flow near the axis of the domain.
The collection of particles in ESP devices involves two major processes (i) particle charging in the unipolar ion region, (ii) particle transport and capture on the collection substrate [19]. Particle charging mechanisms have been a research topic of many investigators: field and diffusion charging expressions [38-41] were developed for large particles (0.3-10 μm), Fuchs [42] and Marlow and Brock’s [43] developed diffusion charging expression for smaller particles and a combined field and diffusion charging expression by Liu and Kapadia [44]. Experimental and numerical studies conducted by several researchers have demonstrated a good agreement in the size range of 0.3-10 μm [45,46]. Multiple experimental studies for the PM in the size range of 30-400 nm [12,14,47,48] agree with theoretical models. Several researchers have also shown that for particles smaller than 30 nm, a fraction of particles was not charged and not collected [49-53]. This is called partial charging. Experimental and theoretical studies conducted by Dey et al. [47], Pui et al. [49], Li et al. [50], Liu and Pui [54] showed that Fuchs theory successfully predicted the charging probability of ultrafine particles. However, there hasn’t been any experimental data or numerical model related to the collection of nanoparticles in high ion concentration and electric field and driven by corona discharge induced flow.

In this manuscript, we describe particle behavior in a needle-to-tube EHD flow. The flow is studied experimentally and by the numerical simulations to resolve the spatiotemporal characteristics of ion concentration, velocity, and electric field. Nanoparticle collection efficiency is determined experimentally at various corona voltages for ambient and NaCl particles. The effect of residence time in the high intensity charging region on the particle charging is elucidated.

II. DESIGN OF A SINGLE-STAGE EHD PARTICLE COLLECTOR

The principle of operation of the single stage particle collector is to aspirate the sample by the corona induced flow, rapidly charge the particles in the charging region, and collect the charged particles on the ground (collection) electrode. The high ion concentration and the strong electric field between the corona and ground electrodes result in efficient charging and high collection efficiencies of particulate matter. FIG. 1 shows the schematic and the principle of operation of the single-stage, two-electrode EHD particle collector. The device consists of a high-voltage needle electrode located and a conductive tube serving as collection electrode. When a high voltage is applied, the neutral air molecules are ionized by the strong electric field at the tip of the corona electrode. In a positive corona discharge, electrons are attracted to the high voltage corona electrode, positive ions such as O_2^+ and O^+ [55] drift towards the cathode. The high-velocity ions are repelled from the high voltage electrode; they collide with the neutral gas molecules driving the EHD flow. Particles enter the charging region (ion drift region) aspirated by the EHD flow traveling through the high electric field, high ion concentration region where high-velocity ions bombard the particle imparting a charge. The Coulomb force caused by the electric field between the corona electrode and grounded collection substrate forces particles towards the inner surface of the collection electrode.

The EHD collector used in this study consists of a corona needle and a ground collection electrode as shown in FIG. 1. The high voltage needle is 0.5 mm thick tungsten
wire with a tip curvature of 1 μm (measured using optical microscopy), the sharp tip resulted in the higher electric field strength and the most consistent EHD flow velocity data. It was shown in the previous studies [56] that needle sharpness affects the generation of corona at lower voltages. The surface of the needle is regularly inspected for pitting using optical microscopy to provide the consistent performance of the device. The ground electrode is an aluminum tubing ID 7 mm with a rounded edge, the radius of curvature is 3 mm; tube length is 25 mm. The electrode holder is fabricated using 3D printing from Polylactic Acid material (PLA). The needle is placed along the axis of the tubing at 3 mm distance from the edge of the tube plane.

**FIG. 1.** Schematic of EHD flow in point to tube electrode setup and particle dynamics in the electro-hydrodynamic flow

### III. EXPERIMENTAL SETUP

The air flow velocity is important in both particle collection as it affects the particle residence time in the high mobility region as well as for equipment design. In the traditional ESPs, severe non-uniformities in the flow profile and in the electrical field causes premature erosion of the collection substrate and reduces the precipitator performance [19,57]. A hot wire anemometer (AN-1005) is used to measure the velocity profile at the outlet of the device. These velocity measurements also serve for calculation of sampling rate of the EHD blower. TSI 1213-20 probe connected to anemometer is placed at the outlet of the device. The anemometer is calibrated for the range of 0.2 m/s to 5 m/s using the standard calibration procedure. The data from the anemometer is collected at a frequency of 10 kHz with a data acquisition module (National Instruments, myRIO-1900) for a sampling time of 10 seconds. A variable high voltage positive power supply (Bertan 205B-20R) is used to create the potential difference between the needle and the grounded tube. The corona current is measured on the cathode using a voltage drop across a 1 MΩ resistor. The onset of corona generation was observed at 2 kV; however, the current measurements in the experiments below 3 kV were not consistent in the day-to-day operations. In this work, the voltage on the needle is varied from 3 kV to 5 kV. For corona voltage above ~6 kV, spark over events occurs. All experiments were performed in ambient air at temperatures of 22-25 C, relative humidity range of 30-35%, and pressure of 1 atm.
Two sets of experiments were performed in this study: (i) ambient particle collection in typical laboratory environment, the particle chemical composition or origin is not known, (ii) collection of NaCl particles generated in the aerosol chamber. The collector was evaluated for two different flow scenarios as shown in FIG. 2. To determine the collection efficiency in the non-EHD flow scenario, the device is connected by a T junction to the ultrafine particle sizer (TSI SMPS 3910) and to an external pump with adjustable flow rate, see FIG. 2(a). This allows determining the device collection efficiency for different flow rates. In the EHD flow scenario, two identical EHD collectors are connected to the particle sizer in parallel. A selection valve allows for sampling from the EHD collector isokinetically or to switch to the parallel device and sample at the flow rates of the EHD collector. The latter measurements are used as the reference for collection efficiency calculations. Electrostatic dissipative tubing is used for fluidic connections. Both reference (no E-field) and EHD collector devices have the identical geometries and fluidic connections. See FIG. 2(b). Particle sizer (TSI SMPS 3910) is used to measure the particle concentrations.

The comparison of particle number concentration from the reference and the EHD collector provides the collection efficiency of the device; similar methodology has been used in previous studies, e.g., [15,58], it can be described by the following expression.

$$\eta = 1 - \frac{C(Voltage,d_p)}{C(no_Voltage,d_p)}$$

(1)
where $\eta$ is the collection efficiency, $d_p$ is the particle diameter and $C$ is the particle concentration. In the current study, the data is recorded based on the measurement for individual size bin, rather than the entire size spectrum scan, to address temporal fluctuation in the particle concentration and size distribution in the environment. Each measurement is repeated at least five times.

In addition to the ambient particles experiments where the morphology and electrical properties of the particle may vary, the performance of the device was characterized using lab generated aerosol particles. Aerosolization of 2% NaCl solution using the MADA Up-Mist™ Medication nebulizer (MADA Products, Carlstadt, NJ, USA) generated particles in the range of 10-150 nm particle diameters. The NaCl collection experiments were performed in a custom 0.3 m$^3$ stainless steel, well-mixed aerosol chamber. The large volume of the chamber with mixing fans provides well-mixed conditions, the aerosol concentration in the chamber was found to be spatially uniformed with the operation of the mixing fans [59]. The sampling time was 60 seconds, and each experiment was repeated for five times to obtain statistically relevant particle size data. The ozone concentration was measured using an ozone analyzer (Model 450, Teledyne Instruments) downstream (25 mm) of the tube over the range of corona voltages. Ozone concentration varies from 14 ppb – 24 ppb for an applied voltage 3 kV – 5 kV.

**IV. MODELING**

The Computational Fluid Dynamics (CFD) modeling is performed to gain insight into the flow properties in the particle collector. Commercial package ANSYS Fluent was used, custom subroutines model two-way coupling of ion motion and fluid flow. FIG. 3 shows the schematic of the modeled geometry. The 2D axisymmetric assumption is used in the numerical simulation.

**FIG. 3.** Computational domain for the numerical simulation; the model includes the ion generation region defined by the thresholds of the electric field

The flow is solved using a finite volume laminar solver; the ion motion equations are solved by adding user-defined scalars to represent the electric potential $\phi$ and charge density $\rho_e$. The electric force’s effect on the flow is solved by introducing a body force $F_e = -\rho_e \nabla \phi$ into the momentum equations, thus the governing equations for the flow are:
\[ \nabla \cdot \mathbf{u} = 0 \quad (2) \]
\[ \rho \frac{D\mathbf{u}}{Dt} = -\nabla P + \mu \nabla^2 \mathbf{u} - \rho \nabla \varphi \quad (3) \]

\( \mu \) is the dynamic viscosity of the air, \( \rho \) is the density of the air, \( \mathbf{u} \) is the velocity vector and \( P \) is the static pressure. The equations for charge transport are:

\[ \frac{\partial \rho_c}{\partial t} + \nabla \cdot \left[ (\mathbf{u} + \mu_b \bar{E}) \rho_c + D_e \nabla \rho_c \right] = S_e \quad (4) \]

\[ \nabla^2 \varphi = -\frac{\rho_c}{\varepsilon_0} \quad (5) \]

where \( \mu_b \) is the ion mobility, which is approximated as a constant \([2.0 \times 10^{-4} \text{m}^2/(\text{V} \cdot \text{s})]\) \([31,32]\) and \( \varepsilon_0 \) is the electric permittivity of free space. \( D_e \) is the ion diffusivity described by the electrical mobility equation (Einstein’s relation) \([31,32]\):

\[ D_e = \frac{\mu_b k_b T}{q} \quad (6) \]

where \( k_b \) is Boltzmann’s constant \((\sim 1.381 \times 10^{-23} \text{J/K})\), \( T \) is the absolute temperature, and \( q \) is the electrical charge of an ion, which is equal to the elementary charge \((1.602 \times 10^{-19} \text{C})\). \( S_e \) is the source term of charge density which has a unit of \( \text{C/m}^3 \cdot \text{s} \). It is calculated from the corona current measured at the anode. In the simulation, the charges are introduced into the computational domain within the ionization zone boundary region at the rate calculated from the anode current. Instead of defining a thin surface within the computational domain to mark as the ionization zone boundary, a region with finite volume is determined by the electric field strength magnitude and constrained within 1mm of the needle tip.

\[ S_e = \begin{cases} 1/\psi, \text{for } |E| \in [E_0, E_1] \text{ and } x_{ip} - x < 1 \text{mm} \\ 0, \text{otherwise} \end{cases} \quad (7) \]

where \( \psi \) is the volume of the region satisfying \( |E| \in [E_0, E_1] \text{ and } x_{ip} - x < 1 \text{mm} \) and \( l \) is the corona current. The \( x_{ip} - x \) term limits the ion production along the needle, in the experiments, the needle tip extends only 1 mm from the needle holder. \( E_0 \) is the critical field below which the number of ions recombination is larger than production per drift length, and it is for air. \( E_i \) is the breakdown electric field strength for air \((3.23 \text{MV/m})\). In fact, both \( E_0 \) and \( E_i \) can be used as the criteria for ionization boundary. Since the charge density is balanced inside the ionization region, the corona current equals to the charge density flux at the ionization boundary. Therefore, by introducing a volumetric flux of charges coming into
the domain, the two ionization boundary conditions are used to mark numerical “ionization region” where the charges (ions) are generated. More details on the treatment can be found in [31]. Numerical schemes and boundary conditions are given in the supplemental information.

V. RESULTS AND DISCUSSION

A. Voltage-Current Characteristics

The corona current and the downstream ion concentration are measured to determine the ion production and ion transport in the device. Table I shows the corona current (anode current) with respect to anode voltage. The current increases with the applied voltage quadratically, which agrees with other results in the literature for different corona configurations [29,30,60-62]. The current values from the experiments were used in the numerical model as the ionization zone boundary condition. In some previous literature, the input charge density was iteratively adjusted to match the measured cathode current, e.g. [26,63]. Here, the cathode current is computed by the code; the numerical model uses corona voltage and anode current as input parameters. The cathode current is determined by integrating the charge flux on the cathode

\[ I_{\text{cathode}} = \int_{\text{area}} -\mu_0 \rho \nabla \phi dA_{\text{cathode}} \]  

where \( I_{\text{cathode}} \) is the cathode current and \( A_{\text{cathode}} \) is the area vector of the cathode.

| Voltage (kV) | Anode current (µA) | The experimental cathode current (µA) | CFD cathode current (µA) |
|-------------|---------------------|-------------------------------------|-------------------------|
| 3           | 0.7                 | 0.62                                | 0.59                    |
| 4           | 3.8                 | 3.34                                | 3.23                    |
| 5           | 7.5                 | 6.68                                | 6.64                    |

The cathode current in the simulation agrees within 5% with the experimental measurements. The cathode recovers 85-90% of the ion current that is generated; the other 10-15% are associated with ions exiting the device. These computed values of cathode current yield good agreement against the experimental data validating the numerical approach with respect to ion concentration field in the ionization and collection regions of the EHD collector.

B. Numerical Results

The numerical approach models the process by which the ion-molecule collisions accelerate the bulk flow. FIG. 4(a) shows the computed electric field lines. The maximum electric field strength is near the tip of the corona needle where a small radius of curvature concentrates the electric field lines; the field intensity reaches the threshold for ion
generation. The effect of the space charge on the electric field is apparent by field line distortions in the region of high ion concentration. These distortions are significantly smaller away from the electrode tip where the charge density is reduced.

**FIG. 4.** Contour plots of the (a) electric field (V/m), (b) ion concentration (#/cc), (c) velocity (m/s) and (d) electric field lines by the non-dimensional parameter for 3 kV corona voltage between the needle and the ground tube. The dash lines on the velocity contour (c) indicate the location at which the velocity of EHD flow is compared with the experiments. The contours of $X$ are clipped to the value of unity; the region with indicates EHD dominated flow.
FIG. 4 (b) shows the ion density contours. The ions are generated at the needle tip, and their motion is dominated by the electric field due to their high electrical mobility, as the ion drift velocity is two orders of magnitude greater than the bulk flow [30,31,64]. Downstream of the charging region, the electric field is weak, especially near the centreline, and ions exit the domain due to high flow velocities. A recirculation zone is formed upstream of the cathode tube near the rounded edge as shown in FIG. 4(c). This is due to the flow expansion which creates an adverse pressure gradient in the near wall acceleration region. To determine the effect of the Coulomb force in the EHD flow, the ratio of electrostatic force to the inertial force is plotted, this ratio is described as a non-dimensional parameter

\[ X = \frac{\rho_e \phi}{\rho u^2} \]  

[31]. FIG. 4(d) shows electric field lines colored by the values of \( X \), indicating the regions where the electric force is greater than inertial force dominating the flow is located between the corona needle and the ground tube.

The particle laden flow passes through the charging region where both ion concentration and electrical field are high resulting in the high collision frequency between the ions and the particle in the flow. The collisions with higher velocity ions result in high particles charging efficiency which leads to higher particle collection. The highest charging rate is at the tip of the electrode as the ion concentration (2.44E+11 #/cc), and electric field strength (7.49E+07 V/m) are the highest. The ion concentration reduces away from the tip due to radial ion motion caused by the ion drift towards ground electrode and the space charge effect. The detailed description of the charging mechanism is not considered in this paper.

**Table II.** Maximum ion concentration and electric field strength in the ionization zone for different applied voltages.

| Voltage (kV) | Ion concentration (#/cc) | Electric field strength (V/m) |
|-------------|--------------------------|-------------------------------|
| 3           | 5.93E+09                 | 5.6E+07                      |
| 4           | 8.62E+10                 | 6.78E+07                     |
| 5           | 2.44E+11                 | 7.49E+07                     |

**C. Velocity Voltage Characteristics**

To validate the EHD modeling approach, the numerical results for corona voltages of \( \phi = 3-5 \) kV are compared with the experimental exit velocities. FIG. 5 shows the velocity profiles plotted for three voltage values. The experiments and numerical results show the maximum velocity is located at the centerline; the profile decays with radial distance. The maximum velocity of the point-to-cylinder corona discharge device is ~4m/s for both experiments and simulations at 5kV corona voltage. At higher voltages arc discharge occurs, the flow velocity drops to zero. The maximum velocities in the numerical simulation are within 10% of the experimental data; the predictions are less accurate at the edges of the domain. The maximum outlet velocity increases linearly with corona voltage. The linear trend of centerline velocity is observed previously in experiments [31,64]. The velocity profiles are similar for all cases. The greater corona voltages result in higher velocities.
FIG. 5. Comparison of velocity profile between the experimental results and simulations at the outlet of the EHD induced flow device as shown in FIG. 4(c).

The velocity profile shows that EHD induced flow in a point-to-tube corona discharge resemble Poiseuille flow near the axis and is significantly different from the pressure-driven flow profile near the walls. The point EHD source generates the flow similar to the submerged laminar jet flow [65]. Laminar flow characteristics are apparent from the experimental data. The Reynolds number (Re) is determined based on the tube diameter and the mean velocity at the exit; $Re \sim 160$ for corona voltage of 3 kV and $Re \sim 400$ for corona voltage of 5 kV. Since the 6 kV cases result in the arc, it appears that the corona induced flow without additional contribution from pressure term remains laminar for the considered internal flow geometry. If any high local Re number regions or flow instabilities are present in the jet at its source, these temporal fluctuations decay by the time the flow reaches the outlet. The calculated flow rates for the EHD driven flow are ~0.8 slpm for 3 kV and ~2 slpm for 5 kV case.

D. Particle Dynamics

Particle behavior in the EHD flow was studied experimentally. FIG. 6 shows the particle collection efficiency of sodium chloride and ambient particles at different corona voltages. The lab generated NaCl particles have higher particle concentration compared to ambient particles. The collection efficiency data is similar for both particle types. The collection efficiency plot can be divided into three distinct regions (i) 10 nm - 20 nm, (ii) 20 nm - 80 nm, and (i) 80 nm - 150 nm.

For all corona voltages, the collection efficiency of particles smaller than 20 nm decreases with the increase of particle size, i.e., the highest collection efficiency for the 10-20 nm range is observed for 10 nm particles. This behavior has not been previously investigated in the literature. The collection efficiency of 10 nm particles increases from 45%
at 3 kV corona voltage to 70% for 5kV corona voltage. These high collection efficiencies indicate that in EHD flow 10 nm particle acquire charge with a higher probability that has been reported. Previous research [42,50-52,66,67] suggests that only small fraction of particles is charged when the particle diameter is less than 30 nm. For example, according to classical diffusion charging models [42,49,50], 12%-37% of 10 nm particle would acquire charges by the thermal ions, and the contribution of the field charging is negligible for this particle size. In our experiments 45%-70% of 10 nm particles were collected thus acquired at least one charge when passed through the charging region of the EHD driven flow. As the corona voltage increases, the ion concentration and the ion mobility (ion velocity) increases leading to more frequent and more energetic collisions with the particles. To the point of the decreasing collection efficiency in the 10-20 nm size range, the previous studies show that it is unlikely for these smaller particles to receive and hold multiple charges [43,49,52]. As the particle size increases from 10 to 20 nm their electrical mobility decreases resulting in the lower collection efficiency.

The particle size range of 20-85 nm exhibits a more traditional behavior; as the particle size increases the collection efficiency increases, likely due to the ability of the particles to carry multiple charges [49-51] resulting in the higher electrical mobility thus, the higher collection efficiency. Here the electrical mobility increases faster than the inertial and the drag forces governing the particle motion. For particle greater than 85 nm, the collection efficiency decreases with the increase of their diameter. The drag and inertial forces on the particle increase resulting in the decrease in the migration velocity even though particles attain multiple charges. This trend is consistent with the previous research showing that for polydisperse particles the collection efficiency reaches a peak and then decreases for larger particles [47,50-52].

![FIG. 6. Size wise particle collection efficiency results for NaCl (unfilled symbols) and ambient particles (filled symbols) at different corona voltages.](image)
To summarize, the trends in the particles collection EHD collector is similar to the previously reported results for particle greater than 20 nm. However, the significantly higher collection of 10 nm particles is observed likely due to the efficient charging in the region of high ion concentration / high electrical field within the corona discharge. The total fraction of particles that acquired at least one charge has not been determined in these experiments, we also do not attempt to quantify the exact number of charges on the particle as a function of ion concentration or electrical field strength; the detailed analytical or empirical model for the dynamic particle charging process in the corona region is not available. In addition to charging model uncertainties, the enhanced charging dynamics in the vicinity of the gas ionization zone may results local surface charge super equilibrium where the charges acquired on the particle surface maybe stripped from the particle by collision with neutral molecules as the particle travels through the domain into the region with less intense E-field with lower charge density.

To gain insight into the conditions in the particle charging region, a series of experiments and multi-physics numerical simulations were performed by varying the particle residence time in the charging zone. The flow rates (thus the residence times) are controlled by the external pump as shown in FIG. 2(a). Though the flow in these experiments is not driven by EHD; all particles travel through the corona discharge region. The residence time is a function of the bulk flow rate as well as the local flow field effect that is affected by the addition if the body force generated by the corona discharge. The results of the numerical simulations are presented in FIG. 7. The baseline case is the EHD driven flow at 5 kV and flow rate of ~2 slpm as determined by both CFD and by integrating the experimental velocity profile. Two additional cases are examined where the flow rates were set to 1 slpm and 5 slpm to investigate higher and lower residence time conditions. The corona induced flow has a significant effect on the velocity profile. FIG. 7 shows the non-dimensional parameter $X$.
for different flowrates is plotted. As the flow rate increases, the inertial term contribution acting on the flow and the particles increases as shown by the smaller region of \( X > 1 \). For the 5 slpm case, this EHD dominated region exist only near the needle tip and in the recirculation vortex caused by the adverse pressure gradient near the wall. The Reynolds number in these cases are: 1 slpm – \( Re \approx 200 \), EHD – \( Re \approx 400 \), 5 slpm - \( Re \approx 1000 \)

**FIG. 8.** Computed velocity profiles in the EHD collector at various axial cross-sections for 5 kV potential difference between the electrodes: a) at the anode electrode (tip of the needle), b) at the cathode electrode (plane aligned with edge of the tube), c) halfway distance between anode and cathode, d) at the exit

The velocity profiles at the cross-sections in the charging zone and at the exit are studied to elucidate the residence time effect on particle collection. FIG. 8(a) shows the velocity profiles at the anode for three different flow rates at a fixed voltage of 5 kV. The higher flow rate reduces the time for the particles to acquire charges as well as the charged particles residence time in the high-intensity electrical field (once the particle sufficiently enters grounded tube the electrical field drops significantly, see FIG. 4(a)). Both of these conditions yield lower collection efficiency. FIG. 8 (b) and (c) shows the velocity profile at
cathode electrode and in between the electrode pair. The velocity profiles have a recirculation region near the wall, the length of the recirculation increases for low flow rates indicating the greater influence of the EHD effect. The corona driven flow produces adverse pressure gradient at the wall due to local flow acceleration at the axis. For the low flow rate cases, particles entering the collector may get trapped in the recirculation regions which increases their residence time in the charging region increasing their collection efficiency. However, in the laminar flow, cross-stream transport is slow (governed by molecular diffusion), and the fraction of total flow entering the recirculation cannot be very high.

![Graph showing particle collection efficiency](image)

**FIG. 9.** Particle collection efficiency as a function of particle size and flow rate for corona voltage of 5 kV

FIG. 9 shows the collection efficiency of ambient particles for 1 slpm, EHD, and 5 slpm cases, the corona voltage for all cases is 5 kV. The collection efficiency trend for particle greater than 20 nm is similar to the data as shown for EHD cases (see FIG. 6). For the 10-20 nm size range, the trends change as a function of the flow rate. As expected, the low flow rate (high residence time) shows overall improved collection for all particles. The trends similar to EHD flow is observed for particles in 10-20 nm range suggesting the high fraction of the particles become charged, and these particles have significant time in the high electric field to be collected onto the ground electrode. The collection efficiency for 10 nm increased from 71% to 85%. Another important data trend is the increase in collection of 20 nm particle from ~40% in the EHD case to ~80% in the 1 slpm case. If it is assumed that 20 nm particle can carry only a single charge, the most likely explanation for doubling the collection efficiency is the increase of particle residence time in the high E-field region due to decrease flow rate from 2 slpm (EHD case) to 1 slpm. The estimation of the particle residence time distribution is difficult as the flow profile is non-uniform, strong recirculation patterns exist in the particle charging region due to the local momentum source. The higher flow rate case is dominated by the pressure driven flow as indicated by the parameter $X$. As the residence time decreases, the collection efficiency of 10 nm drops from 71% to 25% and increases for
the sizes up to 85 nm and then decreases, which similar to previously reported results [47,50-52,67].

The particles with long residence time ~8-10 ms in the charging zone of the flow dominated by EHD (large regions of $X > 1$) have high collection efficiency. As the flow rate increases to 5 slpm, the residence time decreases to ~2-3 ms and it increases to ~17-20 ms for 1 slpm. The fraction of 10-20 nm particles acquiring charge can be as high as 80%. Though additional studies to separate the effects charging and residence time in the high-intensity E-field are needed, here we can conclude that the charging and collection of the ultrafine particles can be enhanced by their prolonged exposure to high charge density – high electric field region.

VI. CONCLUSION AND DISCUSSIONS

This paper provides an experimental and numerical investigation of particle behavior in the electro-hydrodynamic flow. An EHD needle-to-tube electrostatic precipitator aspirates the flow and collects the particle sample onto the collection electrode without the use of an external pump. The experimental data includes voltage, current, velocity profile measurements. Multiphysics numerical simulation shed insight into the interaction of the Coulombic force exerted by the ions on the air flow. The addition of charge flux as a model for the gas ionization zone allows for the direct computation of EHD flow adding the body force to the modified NSE. The numerical simulations agree with experimental data within 10%. The corona induced flow for the investigated internal flow scenarios remains laminar; the $Re = 100$-400 for the range of operating corona voltages. Transition to turbulence is possible with additional pressure contribution, or for greater electrode spacing, however, the transition region was not studied here.

Ambient PM and NaCl ultrafine particle were used to study the particle dynamics in electro-hydrodynamic flow; the collection efficiency is independent of particle type. Measured collection efficiencies in EHD device are in good agreement with the traditional ESPs except for the particles in 10-20 nm range, the collection in the EHD case is significantly higher. The collection efficiency increases for smaller particles likely due to the high fraction of 10-20 nm particles acquiring a unit charge due to high ion concentration and high electrical field in the charging zone. As the particle size increases from 10 to 20 nm, their electrical mobility reduces due to the increase in particle mass while still possessing only a single charge. This hypothesis is further tested by changing the particle residence time in the EHD dominated region ($X > 1$). For the lower flow rate case, the residence time in the charging zone dominated by EHD increases to ~8-10 ms. The collection efficiency and by the extension the fraction of 10-20 nm particles with at least one charge is greater than 80%. The total fraction of the particle that acquired charge has not been determined in these experiments, additional studies to separate the effects charging and collection are needed. The charging and collection of the ultrafine particles can be enhanced by their prolonged exposure to ion bombardment in the high charge density – high electric field region. The first principles modeling approach may shed insight into particle charging mechanism in the EHD flow region.
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NOMENCLATURE

\( \eta \) Collection efficiency of the device
\( d_p \) Particle diameter (nm)
\( C \) Particle concentration (#/cc)
\( \varphi \) Electrical potential (V)
\( \rho_c \) Charge density (C/m\(^3\))
\( F_c \) Electrostatic body force (Pa)
\( \mathbf{u} \) Velocity vector (m/s)
\( \mu \) Dynamic viscosity of air (kg/m\(-s\))
\( \rho \) Density of air (kg/m\(^3\))
\( P \) Static pressure (Pa)
\( \mu_b \) Ion mobility (m\(^2\)/V-s)
\( E \) Electric field (V/m)
\( \varepsilon_o \) Electric permittivity of free space (F/m)
\( D_e \) Ion diffusivity (m\(^2\)/s)
\( S_e \) Source term for charge density (C/m\(^3\)-s)
\( \psi \) Ionization volume (m\(^3\))
\( I \) Anode current (µA)
[\( E_{01}, E_i \)] Electric field criteria limits for ionization boundary (V/m)
\( I_{\text{cathode}} \) Cathode current (µA)
\( A_{\text{cathode}} \) Area vector of the cathode
\( X \) Non-dimensional parameter for the ratio of electrostatic force to inertial force
\( Re \) Reynold number
\( r \) Radial dimension (mm)
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Particle Dynamics in Corona Induced Electro-hydrodynamic Flow

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Supplemental Information

I. COMPUTATIONAL PARAMETERS

Table I shows the numerical schemes used in the CFD calculations. The second order upwind scheme is used to reduce numerical diffusion. The transient laminar solution is computed, the convergence criteria and the simulation time are set to achieve time steady velocity profile at the outlet. Since the ions drift velocity is orders of magnitude greater than the convective flow velocity, the solution for charge transport and electric field converge significantly faster (in convective time) than the flow equations. The boundary conditions are shown in Table II. The total pressure difference between the inlet and outlet is zero as the flow is accelerated only by the ionic drag.

Table I. Numerical schemes

| Model Parameter | Spatial Discretization |
|-----------------|------------------------|
| P-V Coupling    | SIMPLE                 |
| Pressure        | 2nd order upwind       |
| Momentum        | 2nd order upwind       |
| Electric potential | 2nd order upwind     |
| Charge density  | 1st order upwind       |

Table II. Boundary conditions for the numerical simulations

| Boundary       | The value given at the boundary                        |
|----------------|--------------------------------------------------------|
| Inlet pressure | Atmospheric pressure                                    |
| Outlet pressure| Atmospheric pressure                                    |
| Anode needle   | 3~5 kV & Zero diffusion flux for charge                |
| Cathode tube   | 0 kV & Zero diffusion flux for charge                  |
| Wall boundaries| Zero diffusion flux for electric potential & charge density |
II. PARTICLE CONCENTRATION DATA

Two sets of experiments were performed in this study to understand the particle generation from (i) NaCl in distilled solution and (ii) distilled water. Aerosolization of the solutions using MADA Up-Mist\textsuperscript{TM} Medication nebulizer (MADA Products, Carlstadt, NJ, USA) generated particles in the range of 10-150 nm. The experiments were performed in a custom 0.3 m\textsuperscript{3} stainless steel, well-mixed aerosol chamber. The large volume of the chamber with mixing fans provides well-mixed conditions, the aerosol concentration in the chamber was found to be spatially uniformed with the operation of the mixing fans [1]. The sampling time was 60 seconds, and each experiment was repeated five times to obtain statistically relevant particle size data. All the experiments have been performed at a constant relative humidity of 35\%. FIG. 1 shows the particle number density in the distilled water nebulization experiments, the total concentration in the chamber is \(~ 1500 \#/cc. FIG. 2 shows the particle spectra for sodium chloride solution. The particle density for sodium chloride solution experiment is two orders of magnitude greater than during the distilled water nebulization. During NaCl solution nebulization the particle distribution is dominated by the NaCl particles.

\begin{center}
\textbf{FIG. 1.} Particle number density (\#/cc) distribution for distilled water. Majority of the particles are in the size range of 36-86 nm
\end{center}
FIG. 2. Particle number density distribution (#/cc) in sodium chloride experiments.

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