Current-Voltage Characteristics of Unipolar Corona-Needle Charger for Nanoparticles

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Abstract
Particle charger is an important upstream component in the aerosol particle size measurement system by electrical mobility classification in order to impose a known net charge distribution on the aerosol particles. Corona discharge is one of the most commonly technique to produce ion for particle charging. In this study, the corona-needle aerosol charger for unipolar diffusion charging of nanoparticles was designed, constructed, and evaluated. The results of the experimental investigations of the corona discharge of the charger based on current measurements were presented and discussed. It was found that the charging current and ion concentration in the charging zone increase monotonically with corona voltage. The $N_i$ product in the charging zone was found to decrease with aerosol flow rate. The ion number concentrations at the outlet were found to increase with aerosol flow rate at the same corona voltage. It was also shown that the portion of transported ion number concentration from the charger to the Faraday cup is about 7%.

Keywords: Aerosol, Nanoparticles, Aerosol charger, Unipolar charging, Corona discharge

1. Introduction
Aerosol size measurement systems based on electrical mobility technique have been successfully used during the last decades for nanoparticles [1, 2]. Nanoparticles are generally referred to particles of diameter in nanometer size range. One of the most important steps in the electrical mobility aerosol size measurement is the particle charging. The aim of the particle charging is to impose a known net charge distribution on the aerosol particles because prediction of particle size distribution requires the knowledge of the charge distribution for every particle sizes.

Diffusion charging, particles are allowed to collide with ions and the charge carried by these ions is transferred to the particles, is one of the most commonly used mechanisms for charging particles in electrical mobility measurement instruments. There are three conventional ways to produce ions for diffusion charging in a gas. They include; (i) by corona discharge, (ii) by photoelectric/UV-light sources, and (iii) by ionizing radiation from $\alpha$-ray or $\beta$-ray sources such as $^{84}$Kr, $^{241}$Am, and $^{210}$Po [3]. Corona discharge is among the most common technique to produce high ion concentrations and there have been numerous extensive studies in the past [3]. Corona discharge is a low-energy electrical discharge with non-thermal ionization that takes place in the vicinity of an electrode of sufficiently low radius of curvature, in a medium the pressure of which is close to atmospheric [4]. Corona discharge in gases have been applied successfully and several designs of aerosol corona charger are employed and described in the published literature, both corona-wire and corona-needle chargers [3]. Charging efficiency, defined as the fraction of charged particles among all the particles present at the charger downstream, is the most important performance parameter of a particle charger. Aerosol charging is a function of the ion concentration, $N_i$, and the mean residence time of the particles to the ions, $t$.

In this paper, the corona-needle charger for unipolar diffusion charging of nanometer-sized aerosol particles was constructed and evaluated. The results of the experimental investigations of the corona discharge in terms of current-voltage relationships of the corona charger were presented and discussed. A semi-empirical method, based on ion current measurement and electrostatic charging theory, was used to calculate ion concentration in the charging zone and at the outlet of the charger.

2. Experimental Methods
2.1 Description of the Corona-Needle Charger
Schematic diagram of the corona-needle charger used in this study is shown in Figure 1. The charger geometrical configuration is similar to the charger used by Hernandez-Sierra et al. [5], Alonso et al. [6] and Intra and Tippayawong [7]. However, differences exist between the present charger and each of existing chargers by modifying aerosol inlet geometry to ensure uniform particle distribution across the annular aerosol entrance to charging zone.

![Figure 1 Schematic diagram of the corona-needle charger.](image)
In this charger, it consists essentially of a coaxial needle electrode placed along the axis of a cylindrical tube with tapered end. The needle electrode is made of a stainless steel rod, 6 mm in diameter, ending in a sharp tip. The angle of the needle cone is about 10° and the tip radius is about 50 μm, as estimated under a microscope. The outer electrode is made of a stainless steel tube, 30 mm in diameter and 15 mm in length with conical shape. The orifice diameter is about 3 mm. The distance between the needle electrode and the cone apex is 1.5 mm. The corona-needle electrode head is connected to an adjustable DC high voltage supply, while the outer electrode is grounded. A semi-empirical method was used to determine the ion concentrations in the charging zone and the outlet of the charger. The mean ion number concentration, \( N_{i,m} \) in the charging zone of the charger in the absence of aerosol particles is given by [7]

\[
N_{i,m} = \frac{I_d}{eZ_eE_A} \tag{1}
\]

where \( I_d \) is the charging current, \( e \) is the elementary charge \((1.6 \times 10^{-19} \text{ C})\), \( Z_e \) is the mobility of the ions \((1.4 \times 10^{-4} \text{ m}^2/\text{V s} \text{ for positive ions and } 2.2 \times 10^{-4} \text{ m}^2/\text{V s} \text{ for negative ions})\), \( E \) is the electric field inside the charging zone, and \( A \) is the inner surface area of the outer electrode of the charger. The ion number concentration has units of ions/m\(^3\). In this charger, the inner surface area of the metallic cone (charger outlet) where the ion current is collected, is given by [7]

\[
A = \pi (r_1 + r_2) \sqrt{(r_1^2 - r_2^2) + L^2} \tag{2}
\]

where \( r_1 \) and \( r_2 \) are the inner and outer radii of a conical frustum in meters, and \( L \) is the length of the charging zone. If the space charge effect is neglected, the electric field strength was estimated to be given by the simplified equation [7]

\[
E = \frac{V}{d} \tag{3}
\]

where \( V \) is the applied voltage, and \( d \) is the distance between the electrode tip and the cone apex in meters. Particle charging depends on the \( Ni \) product (mean ion number concentration \( \times \) mean aerosol residence time of the aerosol particles spend in the charger). The \( Ni \) product is a fundamental parameter to describe the operation of an aerosol charger, because it is intimately related to the extent to which the particles can become charged. The mean aerosol residence time of the particles in the charging zone of the charger is given by [7]

\[
t = \frac{\pi L \left( r_1^2 + r_2 r_1 + r_2^2 \right)}{3Q_e} \tag{4}
\]

where \( Q_e \) is the aerosol flow rate. The ion number concentration at the charger outlet, \( N_{i,out} \) can be calculated from the expression [7]

\[
N_{i,out} = \frac{I}{eQ_e} \tag{5}
\]

where \( I \) is the ion current at the charger outlet. The ion current measurements were translated into ion number concentrations given the total air flow rate through the charger.

### 2.2 Experimental System

The schematic diagram of the experimental setup for the electrical discharge characterization of the corona-needle charger used in this study is shown in Figure 2. Clean dry air flow was regulated and controlled by means of a mass flow meter and controller, typically in the range between 1.0 – 5.0 L/min. The air flow was forced by a vacuum pump. A commercial adjustable DC high voltage power supply, a Leybold Didaetic model 521721, was used to maintain the positive corona voltage difference in the charger, generally in the range between 1.0 – 5.0 kV. The charging current from the corona-needle electrode was measured directly with the sensitive electrometer, Keithley 6517A electrometer incorporating a Keithley 6522 scanner card, via the outer electrode. In this study, the ion current at the charger outlet was measured by filtration method. An air sample was drawn into a shielded Faraday cup with a filter through which all the air passed. The filter was equipped with a fine collection metal grid, and was electrically isolated from the Faraday cup and ground. High efficiency particulate-free air (HEPA) filter was used for these experiments because the collection efficiency for small air ions was very high. In the Faraday cup, the charges were removed from the air stream by the filter and the resulting ion current flow was monitored with the electrometer.

### 3. Results and Discussion

Figure 3 shows current-voltage characteristics in the charging zone of the charger. In this charger, the corona onset was found about 2.2 kV. Increase in corona voltage produced a monotonic increase in charging current.
It was shown that the spark-over phenomena occurred for the corona voltages larger than about 4.2 kV. Above these values, the current was found to exhibit a fluctuation in an uncontrollable manner and no measurement could be made. The variation in ion number concentration with corona voltage in the charging zones of the charger is shown in Figure 4. The ion concentration was approximately proportional to the charging current. It was found that the ion concentration in the charging zone increases with increasing corona voltage. The corona voltage variation of the $N_I$ product in the charging zone of the charger for different operating aerosol flows was shown in Figure 5. The resultant $N_I$ products were evaluated for 1.0 – 5.0 L/min and 1.0 – 4.5 kV. The obtained results were expected for the effects of aerosol flow and corona voltage. Higher aerosol flow rate, hence shorter residence time gave rise to lower $N_I$ product. Increase in corona voltage produced a monotonic increase in ion number concentration, hence the $N_I$ product. Figure 6 shows the variation in ion current and number concentration of the charger outlet with corona voltage at different operating aerosol flow rate.

Increase in aerosol flow rate resulted in the increase of the ion number concentration with the same corona voltage. It was found that the ion concentrations increase with increasing corona voltage only within a narrow voltage interval. For larger voltages, ion number concentrations decreased slightly with increasing corona voltage. The highest ion current in the Faraday cup was found about $1.1 \times 10^{-10}$ A corresponding to the ion number concentration is about $8 \times 10^{12}$ ions/m$^3$, occurring aerosol flow rate at 5 L/min and corona voltage of 3 kV. Conversely, the maximum charging current from the corona-needle charger under the same conditions is about $5.7 \times 10^6$ A corresponding to the ion number concentration is about $1.2 \times 10^{15}$ ions/m$^3$. Hence only 7% of the ion number concentration emitted by the corona-needle is transferred to the Faraday cup. This was expected that when the corona voltage increased, electric field strength in the charging zone were found to increase, inducing a better particle charging rate and more ions loss due to deposition on the inner surface of the outer electrode inside the charger.
4. Concluding Remarks

In this study, corona-needle charger for unipolar corona-needle charger of nanometer-sized aerosol particles was designed, constructed, and experimentally evaluated in terms of current-voltage characteristics. A semi-empirical method based on current measurements was used to determine average ion concentration in the charging zone and at the outlet of the charger. Charging current, ion number concentration, and $N_{i}$ product as a function of corona voltage and aerosol flow rate were evaluated. It was found that the charging current, ion concentration, and $N_{i}$ product in the charging zone increase with increasing corona voltage. The $N_{i}$ product in the charging zone was found to decrease with aerosol flow rate. The ion current and ion number concentration at the charger outlet were found to increase with aerosol flow rate at the same corona voltage. It was also shown that the portion of transported ion number concentration from the charger to the Faraday cup is about 7%.

Finally, the unipolar corona-needle charger examined in this study constitutes, therefore, a simple and useful device to produce relatively high concentrations of unipolarly ions for nanoparticles charging.

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References

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