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Design and Evaluation of a High Concentration, High Penetration Unipolar Corona Ionizer for Electrostatic Discharge and Aerosol Charging

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Abstract – The aim of this paper is to design and evaluate a high concentration, high penetration unipolar corona ionizer. The electrostatic characteristics in terms of voltage-current relationships of the present ionizer in the discharge zones for positive and negative coronas were discussed. Using ion current measurement, the concentration and penetration of ions were evaluated at corona voltages across the needle electrodes between 1 and 4 kV, flow rates between 1 and 5 L/min, and an operating pressure of 1 atm. In the discharge zone of the ionizer, the highest ion concentrations were found to be about 1.71×10^{14} and 5.09×10^{14} ions/m^3 for positive and negative coronas, respectively. At the outlet of the ionizer, it was found that the highest ion concentration was about 1.95×10^{13} and 1.91×10^{13} ions/m^3 for positive and negative coronas, respectively. The highest ion penetration for positive and negative coronas through the ionizer was found to be about 98 % and 33 %, respectively. The N_it product for positive and negative coronas was also found to 1.28×10^{13} and 7.43×10^{13} ions/m^{3}s, respectively. From the findings, this ionizer proved to be particularly useful as an aerosol charger for positive and negative charge before the detector in an electrical aerosol detector.

Keywords: Aerosol, Ion, Corona Discharge, Ionizer, Unipolar Charging

1. Introduction

Aerosol charging is the first basic step in the aerosol measurement based on electrostatic technique [1]. The objective of the aerosol charging mechanism for an electrical aerosol detector is to impose a known net electric charge on the aerosol particles because number concentration of particles depends on the mean charge level of aerosol particles as a function of particle diameter and the mean residence time of the particles to the ions [2]. There are many mechanisms by which aerosol particles acquire net electric charge. There are several mechanisms by which aerosol particles acquire net charge distributions. These are flame charging, static electrification, diffusion charging and field charging [3]. Diffusion charging is one of the most commonly used mechanisms for charging particles in electrical measurement instruments. Generally, aerosol particles are allowed to collide with ions and the charge carried by these ions is transferred to the particles. There are three conventional ways to produce ions for diffusion charging in a gas; (i) by corona discharge, (ii) by photo-electric/UV-light sources, and (iii) by ionizing radiation from α-ray or β- particle sources such as ^{85}Kr, ^{241}Am, and ^{210}Po.

However, corona discharges are among the most common techniques to produce high ion concentrations and there have been numerous extensive studies in the past [4-13]. Corona discharge is produced by a non-uniform electrostatic field such as that between a needle and plate or a concentric wire and a tube. In this corona region, electrons have sufficient energy to knock an electron from gas molecules creating positive ions and free electrons. During this process, aerosol flow is directed across the corona discharge field and is charged by random collisions between the ions and particles due to Brownian motion of ions in space. The amount of ion deposition on the particle surface depends on resident time, particle radius and shape, electric field, etc. This technique has been applied successfully and several designs of aerosol corona ionizer have been employed and described in the published literature [14], both corona-wire and corona-needle ionizers. A widely used ionizer is a corona-needle dischargers because of its simplicity and capability to provide high number concentrations of ions [15]. There have been numerous studies and developments on the corona-needle ionizer, both AC and DC sources [5, 10-12]. In general, the ideal charger would need a high efficiency charging technique that: (a) produces stable and high ion concentrations, (b) does not damage the aerosol, (c) has low particle losses (d) has no contamination, (e) applies to nanoparticles, and (f) is capable of working at low

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pressures and in different gases. The geometry, dimension and size of the precipitator should be less complex to keep the unit cost low.

This paper presents the work on designing and evaluating the high concentration, high penetration unipolar corona ionizer for electrostatic discharge and aerosol charging. The electrostatic characteristics in terms of voltage-current relationships of the present ionizer in the discharge zones for positive and negative coronas were discussed. Its electrostatic characteristics were determined at corona voltages at the needle electrode between 1 and 4 kV, flow rates between 1 and 5 L/min, and an operating pressure of 1 bar. Based on ion current measurement, the concentration and penetration of ions of the ionizer were also evaluated.

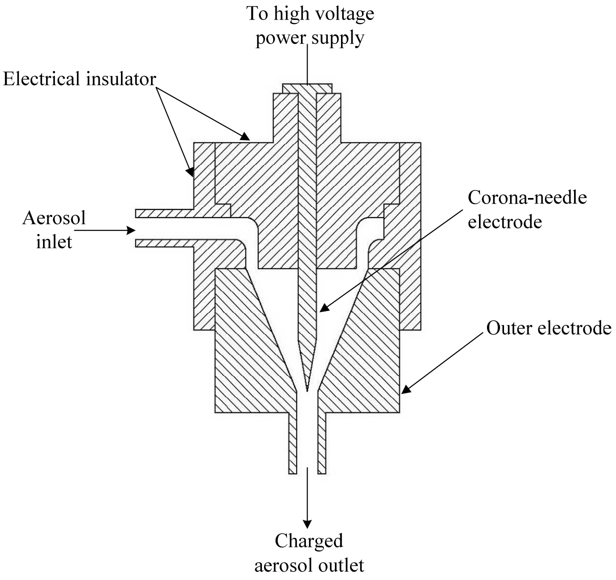

Fig. 1. Schematic diagram of the corona-needle ionizer.

2. Description of Unipolar Corona Ionizer

Fig. 1 shows the schematic diagram of the corona-needle ionizer employed in this study. The ionizer's geometrical configuration is similar to the ionizer used by Whitby [5], Hernandez-Sierra et al. [10], Alonso et al. [11], and Intra and Tippayawong [12]. However, differences between the present ionizer and existing ionizers include; (i) the concept of the present ionizer was based on a compact, inexpensive and portable unit. Short column ionizer was used to reduce diffusion effects of the particle inside the ionizer; (ii) the ionizer adopted a tangential aerosol inlet upstream of the charging zone to ensure uniform particle distribution across the annular aerosol entrance to the charging zone of the ionizer column; and (iii) the applied voltage was set to maintain at low level to reduce electrostatic precipitation effects of the particle inside the ionizer. In general, the electrostatic discharge and ionization of the ionizer was dependent on the geometrical configuration, the charging time, the electric field strength and the flow field and behavior of the ionizer. A comparison between the present ionizer and the existing ionizers in terms of the geometrical configuration, the aerosol flow rate, the corona voltage range and the aerosol flow behavior is shown in Table 1. It was shown that the present ionizer is more compact, and operates at lower applied voltage than existing ionizers.

The present ionizer consists essentially of a coaxial needle electrode placed along the axis of a cylindrical tube with tapered end, and divided into three sections. The first and second sections (from top to bottom in the drawing) are made of a polytetrafluoroethylene (PTFE), and the third (outlet section) of stainless steel tube. The PTFE tube is an electrical insulator between needle electrode and outer electrode and served to hold the needle electrode coaxial with the outer electrode. The needle electrode could be screwed into the PTFE insulator to connect to a DC voltage supply. The needle electrode is made of a stainless steel rod, 3 mm in diameter, ending in a sharp tip. The tip radius is about 50 μm, as estimated under a microscope. The needle cone angle is about 10^o. The diameter of the outer electrode is 20 mm, its length is 20 mm with conical shape. The orifice diameter is about 3.5 mm. The distance between the needle electrode and the cone apex is 1.75 mm. The needle electrode head is connected to a positive high voltage, while the outer electrode is grounded.

3. Theory

3.1 Ion Number Concentration of the Ionizer

In the absence of aerosol particles, the mean number

Table 1. Comparison of different unipolar corona-needle ionizers.

Reference	Needle electrode diameter	Electrodes distance	Discharge zone length	Aerosol flow rate	Corona voltage range	Aerosol/ion direction
Whitby [5]	n/a	n/a	n/a	0 – 70 L/min	0 – 9.0 kV	Perpendicular
Hernandez-Sierra *et al.* [10]	3.0 mm	4.0 mm	55 mm	0 – 10 L/min	2.5 – 4.0 kV	Perpendicular
Alonso *et al.* [11]	n/a	3.5 mm	25 mm	0 – 10 L/min	3.1 – 3.7 kV	Circular
Intra and Tippayawong [12]	6.0 mm	3.5 mm	30 mm	0 – 8 L/min	2.6 – 4.3 kV	Circular
This work	3.0 mm	3.5 mm	20 mm	0 – 5 L/min	2.2 – 3.6 kV	Circular

n/a: information not available

concentration of ions, n_{in}, in the discharge zone of the ionizer can be estimated from the discharge current using the expression [12]

$$n_{in} = \frac{I_{in}}{eZ_i EA} \tag{1}$$

where I_{in} is the current deposited on the grounded conical-shaped wall, e is the elementary charge, Z_i is the electrical mobility of the ions (It has been suggested that the average value for the positive and negative ion electrical mobility at atmospheric pressure were $Z_i^+ = 1.4 \times 10^{-4}$ m^2/V s and $Z_i^- = 2.2 \times 10^{-4}$ m^2/V s, respectively [16]), E is the electric field inside the discharge zone, and A is the inner surface area of the metallic cone (ionizer outlet) where the discharge current is collected. In the present ionizer, the inner surface area of the metallic cone (charger outlet) where the ion current is collected, and is given by

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

where r_1 and r_2 are the inner and outer radii of a conical-frustum, and L is the length of the discharge zone of the ionizer. The ion number concentration has units of ions/m^3. The mean residence time or charging time of the particles in the charging zone of this charger is given by

$$t = \frac{\pi L\left(r_1^2 + r_1 r_2 + r_2^2\right)}{3Q_a} \tag{3}$$

where Q_a is the volumetric air flow through the ionizer.

The total number concentration of ions at the ionizer outlet, n_{out}, can be calculated from the ion current by the following equation [10]

$$n_{out} = \frac{I_{out}}{eQ} \tag{4}$$

where I_{out} is the ion current at the ionizer outlet was measured by the Faraday cup electrometer, and Q is the volumetric air flow through the Faraday cup.

3.2 Ion penetration through the ionizer

The ions penetration, P, through the ionizer is defined as the ratio of the number concentration of ions at the ionizer outlet over the number concentration of ions in the discharge zone of the ionizer, and can be estimated from the relation [12]

$$P = \frac{n_{out}}{n_{in}} \tag{5}$$

4. Experimental Setup and Apparatus

The schematic diagram of the experimental setup for the electrostatic discharge characterization of the present ionizer is shown in Fig. 2. Air flow was regulated and controlled by means of a mass flow controller (Dwyer model GFC-1111) with a vacuum pump, typically in the

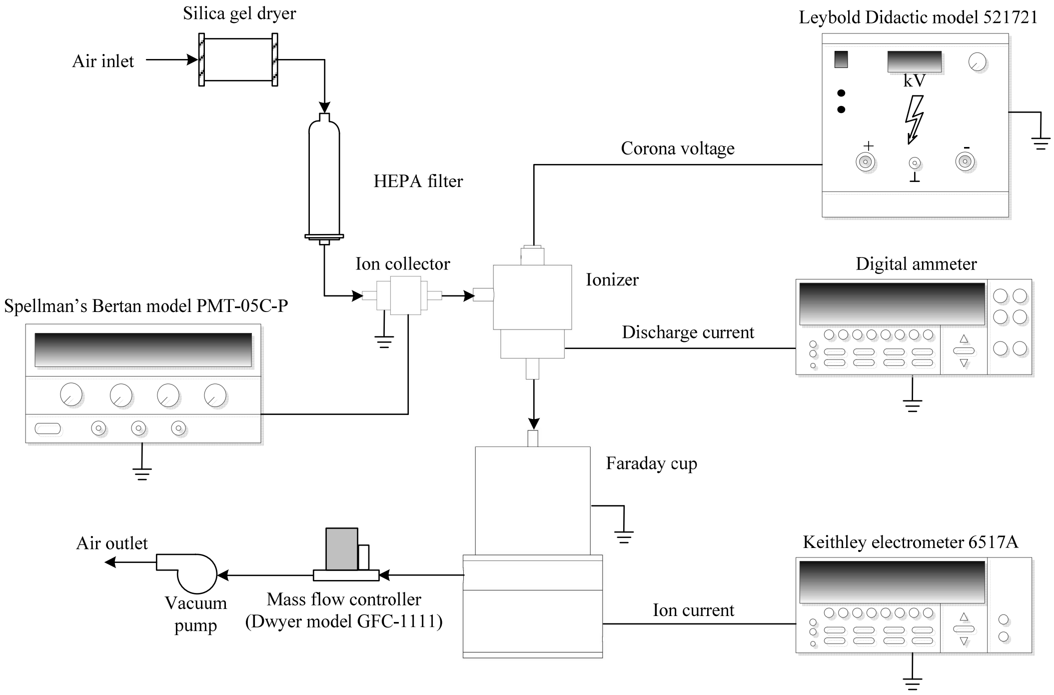

Fig. 2. Experimental setup for the characterization of the corona-needle ionizer.

Table 2. Ranges and values of variables investigated.

Variable	Range
Corona voltage	0 – 4 kV
Orifice diameter	3.5 mm
Needle cone angle	10^o
Ion generated	positive ion (+), negative ion (–)
Ionized gas	air
Flow rate	1, 3 and 5 L/min
Pressure	1 atm

range between 1.0 – 5.0 L/min. The air was first dried with the diffusion dryer, any remaining water was removed, and then filtered through a high efficiency particulate-free air (HEPA) filter, Pall HEPA capsule model 12144 with filtration efficiency of 99.97 % and retention of 0.3 μm for air/gas, to remove any particles and then enter the ion trap to remove the air ions. A commercial adjustable DC high voltage power supply (Leybold Didactic model 521721) was used to maintain the positive high voltage difference in the ionizer, generally in the range between 1.0 – 4.0 kV. The discharge current from the corona-needle electrode was measured directly with a digital ammeter. The rate of discharging is proportional to the mean ion number concentration in the discharge zone.

In this study, the ion current at the ionizer outlet was measured by filtration method. An air sample was drawn into a shielded Faraday cup with a HEPA filter through which all the air passed. A Faraday cup was devised using a 47 mm stainless steel filter holder in a 70 mm diameter stainless steel container. The filter was equipped with a fine collection metal grid, and was electrically isolated with Teflon from the container and ground. In the Faraday cup, the 99.99 % of ions were removed from the air stream by the filter and the resulting ion current flow was measured with Keithley 6517A electrometer. The filter holder was connected to the electrometer input that had been carefully shielded against external fields. Triaxial cables (Keithley 237-ALG-2) between the Faraday cup and the electrometer eliminated leakage currents. As shown in Table 2, several sets of experiments were carried out at varying corona polarity and voltage and aerosol flow rates. For each set of operating conditions, measurements were repeated at least three times.

5. Results and Discussion

Fig. 3 shows the current-voltage characteristics in the discharge zone of the ionizer for positive and negative ions. The corona voltage was varied from 0 to 4 kV, the flow rate of 0 L/min, and operating pressure of 1 bar. It was found that the discharge currents increased monotonically with an increase in the corona voltage. The corona onset voltages were found to be about 2.4 and 2.2 kV for positive and negative ions, respectively. As shown in the plot, the spark-over phenomena occurred for the positive corona at voltages larger than 3.6 kV at discharge current of about 2.8×10^{-5} A and negative corona voltages larger than 3.0 kV at discharge current of about 7.8×10^{-5}A. The spark-over phenomena marks electrical breakdown of the gas were observed to release higher discharge current corresponding to ion concentration, but it was undesirable because of higher particles loss inside the ionizer due to high electrostatic field. Above these values, the discharge current was found to exhibit a fluctuation in an uncontrollable and unstable manner. No measurement could be made by available digital ammeter because of higher discharge current of several hundred mA flowing through the air gap between the electrodes. At the same voltage, the currents for negative ions were slightly higher than those positive ions. This was expected because negative ions have higher electrical mobility than positive ones. It was more likely to mpact and deposit on the outer electrode wall of the ionizer due to the electrostatic force [16].

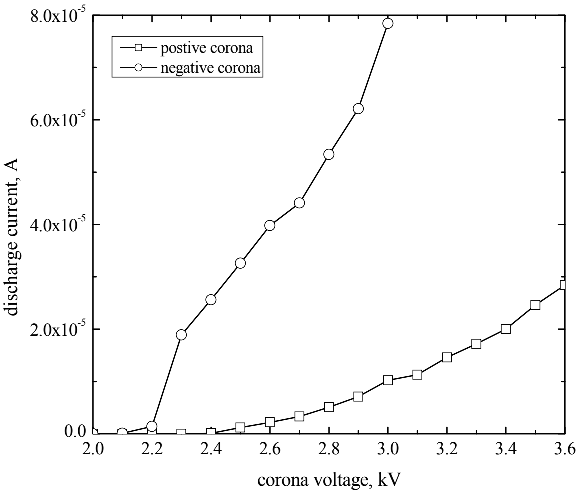

Fig. 3. Current-voltage characteristics in the discharge zone of the ionizer.

For different operating flow rates, the current-voltage characteristics in the discharge zone of the ionizer are shown in Fig. 4. The resultant discharge currents in the discharge zone of the ionizer for both positive and negative coronas were evaluated for 0, 1, 3 and 5 L/min, and 0 – 4 kV. Discharge current for positive corona voltage practically became constant, independent of the flow rate. Meanwhile, negative discharge currents were found to depend on flow rate, increased with increasing flow rate, because higher electrical mobility and ion will be moved toward outer electrode by air flowing. However, the electrical breakdown voltages were found to decrease with increasing flow rate for both positive and negative coronas. It was expected that the ion or electron will be accelerated quickly from corona electrode to outer electrode with higher flow velocity according to the flow rate.

With respect to the current-voltage characteristics, the variation in ion number concentration with corona voltage in the ionizer discharge zone at different operating flow

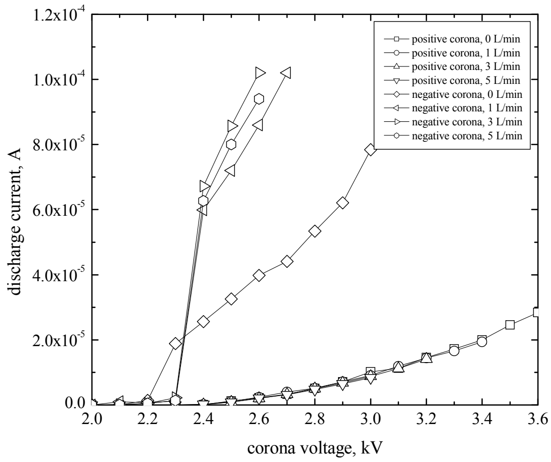

Fig. 4. Current-voltage characteristics in the discharge zone of the ionizer at different operating flow rates.

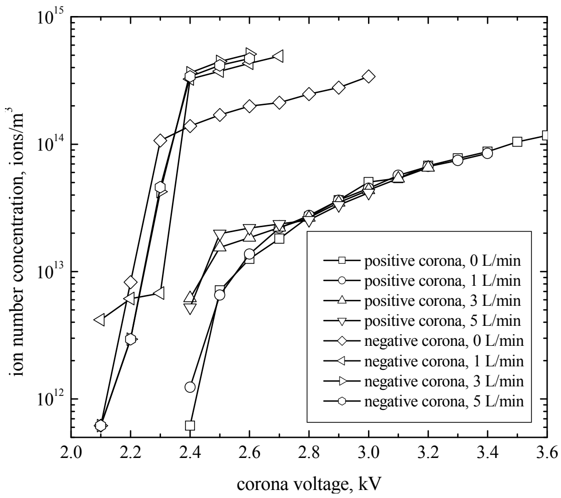

Fig. 5. Variation in ion number concentration with corona voltage in the ionizer discharge zone at different operating flow rates.

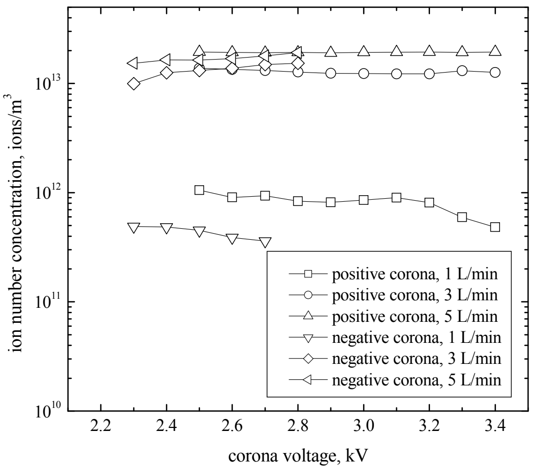

Fig. 6. Variation in ion number concentration with corona voltage at the ionizer outlet.

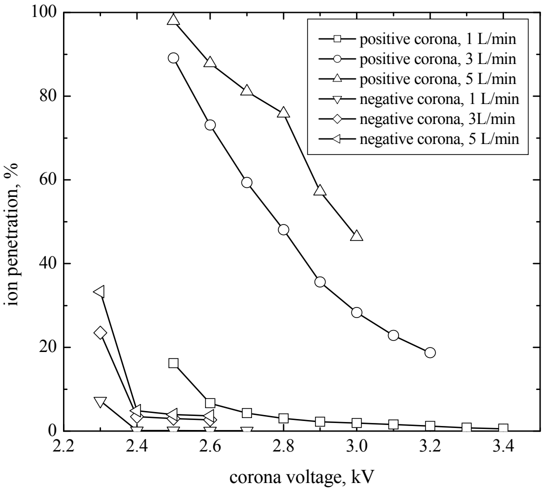

Fig. 7. Variation of ion penetration with corona voltage at different operating flow rates.

rates is shown in Fig. 5. The mean number concentration of ions in the discharge zone of the ionizer was calculated by Equation (1). Obviously, the increase of the ion number concentration depends on the corona voltage. This shows that the highest ion concentration for positive and negative coronas was about 1.71×10^{14} and 5.09×10^{14} ions/m^3, occurring at corona voltage of about 3.6 and 2.6 kV, respectively. It is commonly known that the number concentration of negative ion is generally larger than positive ion, in a range well above corona onset. Fig. 6 shows the number concentration of positive and negative ions as a function of the corona voltage at the ionizer outlet at operating flow rate between 1 and 5 L/min. The onset voltage for negative corona appeared at about 2.3 kV, while positive corona was needed for the onset voltage of about 2.5 kV. At the flow rate of 1 L/min, it was found that the ion concentration for both positive and negative coronas decreased with increasing corona voltage. For larger operating flow rate, ion number concentration for positive corona practically became a constant, independent of the corona voltage, while negative corona slightly increased with increasing corona voltage, dependent of the corona voltage in narrow range. The highest ion concentration was found to be about 1.95×10^{13} and 1.91×10^{13} ions/m^3 occurring at the corona voltage of 3.4 and 2.8 kV for positive and negative coronas, and the flow rate at 5 L/min, respectively.

Fig. 7 shows the ion penetration as a function of the corona voltage at different operating flow rates. Both positive and negative coronas, the penetration dropped with increasing corona voltage because the sink flow of air through the discharge zone was no longer able to focus all of ions through the discharge zone and more ions loss due to electrostatic deposition on the inner surface of the outer electrode inside the ionizer. When the flow rate increased, the ion penetration through the ionizer was found to

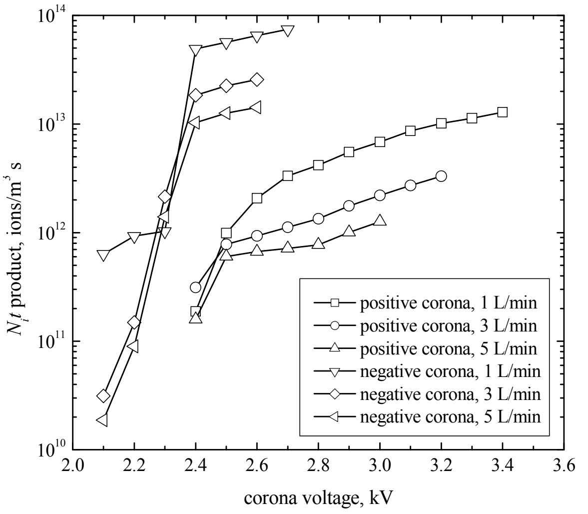

Fig. 8. Variation of $N_i t$ product with corona voltage at different operating flow rates.

slightly increase. This is because the ions can be transported from the ionizer more easily by faster flowing air. Due to high electrical mobility of negative ion, the penetration of positive ions was found to be higher than negative ions. From Fig. 7, the highest ion penetration for positive and negative coronas through the ionizer was found to be about 98 %, and 33 % occurring at the corona voltage of 2.5 and 2.3 kV, and the flow rate of 5 L/min, respectively. For most applications of the ionizer, stability and the absolute magnitude of the free ion current are more important than the efficiency as long as the efficiency is high.

It should be noted that the aerosol charging efficiency depends on the product of the ion number concentration and the average time the aerosol particles spend in the ionizer. Fig. 8 shows the variation of $N_i t$ product (product of ion concentration and charging time) with corona voltage at different operating flow rates. In this study, the charging times were found to be about 0.15, 0.05 and 0.03 sec for the flow rates of about 1, 3 and 5 L/min, respectively. It was shown that the $N_i t$ product decreased with increasing flow rate because higher flow rate or shorter residence time gave rise to lower $N_i t$ product. Increase in corona voltage produced a monotonic increase in ion number concentration, hence the $N_i t$ product. It was also shown that the highest $N_i t$ product for positive and negative coronas was found to 1.28×10^{13} and 7.43×10^{13} ions/m^3 s occurring at the corona voltage of about 3.4 and 2.7 kV, and the flow rate of 1 L/min, respectively.

6. Conclusion

The high concentration, high penetration unipolar corona ionizer for electrostatic discharge and aerosol charging was designed and electrostatically evaluated. The electrostatic characteristics in terms of voltage-current relationships of the present ionizer in the discharge zones for positive and negative coronas were discussed. The concentration and penetration of ions of the ionizer were evaluated based on ion current measurement. The experiments were carried out at corona voltages at the needle electrode between 1 and 4 kV, flow rates between 1 and 5 L/min, and an operating pressure of 1 atm. In the discharge zone of the ionizer the highest ion concentration for positive and negative coronas was about 1.71×10^{14} and 5.09×10^{14} ions/m^3 occurring at corona voltage of about 3.6 and 2.6 kV, respectively. At the outlet of the ionizer, it was found that the highest ion concentration was found to be about 1.95×10^{13} and 1.91×10^{13} ions/m^3 occurring at the corona voltage of 3.4 and 2.8 kV for positive and negative coronas, and the flow rate at 5 L/min, respectively. The highest ion penetration for positive and negative coronas through the ionizer was found to be about 98 %, and 33 % occurring at the corona voltage of 2.5 and 2.3 kV, and the flow rate of 5 L/min, respectively. The $N_i t$ product for positive and negative coronas was also found to 1.28×10^{13} and 7.43×10^{13} ions/m^3 s occurring at the corona voltage of about 3.4 and 2.7 kV, and the flow rate of 1 L/min, respectively. Finally, this shows that this ionizer proved to be particularly useful as an aerosol charger for positive and negative charge before the detector in an electrical aerosol detector.

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