Approach to Characterization of a Diode Type Corona Charger for Aerosol Size Measurement

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Abstract - A semi-empirical method to determine the electrostatic characteristics of a diode type corona aerosol charger based on ion current measurement and electrostatic charging theory was presented. Results from mathematical model were in agreement with those from experimental investigation of the charger. Current-voltage characteristics, N_it product and charge distribution against aerosol size were obtained. It was shown that the space charge was significant and must be taken into account at high ion number concentration and low flow rate. Additionally, significant particle loss was evident for particles smaller than 20 nm in diameter where their electrical mobility was high. Increase in charging efficiency may be achieved by introducing surrounding sheath flow and applying AC high voltage. Overall, the approach was found to be useful in characterizing the aerosol charger.

Keywords: aerosol, corona, charger, unipolar charging

1. Introduction

Corona discharges are among the most common techniques to produce high ion concentrations and there have been numerous extensive studies in the past. The phenomenon is used in many industrial applications such as electrostatic coating and precipitation[1]. Electrostatic charging by the corona dischargers is also commonly used in determining aerosol size distribution by electrical mobility analysis. 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. The process can be characterized as unipolar or bipolar depending on the polarity of the ions in the gas. The technique has been applied successfully and several designs of wire-cylinder corona charger are employed and described in the published literature, both wire-cylinder corona[2–4] and needle chargers[5]. A number of particle sizing instruments employ unipolar corona chargers[6–10] as important upstream component to impart known charge to the aerosol system. The charger performance of these instruments depends on the stable operation of their chargers. Aerosol charging is a function of the ion concentration, N_i, and the mean residence time of the particles to the ions, t. For this reason, a well-designed corona charger should provide a stable N_it product that can be accurately determined for any given operating conditions.

In the present study, the diode type corona charger was chosen. The main advantages of this charger type are the high efficiency and the simple construction. The electrostatic characteristics of the corona charger were evaluated at different operating conditions. A semi-empirical method was used based on ion current measurement and electrostatic charging theory. Average and spatial distribution of ion concentrations in the charging region of the corona charger were calculated. The space charge effect was also considered. Distribution of the N_it product as well as particle penetration and average elementary charge on particle against its diameter were computed and discussed.

2. Theory

2.1 Spatial Distribution of Ion Concentration

Derivation of the theoretical current-voltage relation proceeds from Poisson's equation which governs all electrostatic phenomena and is given as [11]

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0} \tag{1}$$

where V is the applied voltage, ρ is the space-charge density, and ε_0 is the dielectric constant of vacuum (8.854×10^{-12} F/m). Assuming no axial variation, the above equation can be expressed in cylindrical coordinates as

$$\frac{1}{r}\frac{dV}{dr}\left(r\frac{dV}{dr}\right)+\frac{\rho(r)}{\varepsilon_0}=0 \tag{2}$$

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Considering that the ion current density is

$$\vec{j} = \rho \vec{u}_i \quad (3)$$

where $u_i(r) = Z_i E(r)$ is the mean ionic velocity, the space-charge density for the cylindrical corona is given by

$$\rho(r) = \frac{I_{\text{ion}}}{2\pi r L Z_i E(r)} \quad (4)$$

where

$$E(r) = -\frac{dV}{dr} \quad (5)$$

Noting that $j = I_{\text{ion}} / 2\pi r L$. I_{ion} is the measured ion current at distance r from the corona-wire in the charger with charging length L, and Z_i the electrical mobility of the ions. Substituting $\rho(r)$ and $E(r)$ into equation (2) gives

$$rE(r)\frac{dE(r)}{dr} + E(r)^2 - \frac{I_{\text{ion}}}{2\pi L \varepsilon_0 Z_i} = 0 \quad (6)$$

This equation is readily integrated to

$$E(r) = \sqrt{\frac{I_{\text{ion}}}{2\pi L \varepsilon_0 Z_i} + \frac{c}{r^2}} \quad (7)$$

This describes the electric field under space charge conditions where c is the integration constant which is constrained to the interval

$$\left(-\frac{I_{\text{ion}} r_1^2}{2\pi \varepsilon_0 L Z_i}\right) \le c \le \left(\frac{V}{\ln(r_2/r_1)}\right)^2 \quad (8)$$

The space charge can, at most, compensate the electric field at the inner electrode to zero. The limiting case, $E(r_1) = 0$, corresponds to the lower limit for c. The other extreme of no space charge implies that $I_{\text{ion}} = 0$ and the expression for the electric field in a concentric electrode gap, if the space charge effect is neglected, is determined by

$$E(r) = \frac{V}{r \ln(r_2 / r_1)} \quad (9)$$

Inserting $E(r)$ in equation (7) gives the upper limit for c. The integral equation (7) along the radial distance in the charging region of the charger is equal to the voltage difference

$$V = \int_{r_1}^{r_2} E(r)dr \quad (10)$$

The integration limits for the case of the ion generation zone are the corona-wire r_1 and the outer electrode r_2 radii, respectively. In the same way, V is the voltage difference between the corona-wire and the outer electrode of the charger. Integrating the above equation results in

For c > 0

$$V = \left| \begin{array}{l} \sqrt{\frac{I_{\text{ion}}}{2\pi L \varepsilon_0 Z_i} r^2 + 2c} \\ + \frac{c}{\sqrt{2c}} \ln \frac{\sqrt{\frac{I_{\text{ion}}}{2\pi L \varepsilon_0 Z_i} r^2 + 2c} - \sqrt{2c}}{\sqrt{\frac{I_{\text{ion}}}{2\pi L \varepsilon_0 Z_i} r^2 + 2c} + \sqrt{2c}} \end{array} \right|_{r_1}^{r_2} \quad (11)$$

For c < 0

$$V = \left| \begin{array}{l} \sqrt{\frac{I_{\text{ion}}}{2\pi L \varepsilon_0 Z_i} r^2 + 2c} \\ + \frac{c}{\sqrt{-2c}} \arccos \frac{1}{r} \sqrt{-\frac{4c\pi \varepsilon_0 L Z_i}{I_{\text{ion}}}} \end{array} \right|_{r_1}^{r_2} \quad (12)$$

The electric field strength at the surface of the wire at corona discharge onset, E_0, has been experimentally evaluated by Peek [12] and fitted empirically by relation as

$$E_0 = E_s(\delta + A\sqrt{\delta / r_1}) \quad (13)$$

where

$$\delta = \frac{T_r}{T}\frac{P}{P_r} \quad (14)$$

E_s denotes the breakdown field in air at normal conditions (3.10×10^6 V/m for negative corona, and 3.37×10^6 V/m for positive corona, at standard temperature and pressure), A is a dimensioned constant (0.0308 $m^{1/2}$ for negative corona, and 0.0241 $m^{1/2}$ for positive corona), δ is the relative density of air relative to normal conditions (1.205 kg/m^3 for air), T_r is the absolute temperature of room air, P_r is the normal atmosphere pressure, and T and P are the operating temperature and pressure of the air. If space-charge effect is neglected, the corona onset voltage V_0 can be calculated from equation (9) as

$$V_0 = E_0 r_1 \ln(r_2 / r_1) \tag{15}$$

The average current density j at the outer electrode surface area as a function of the potential at the corona discharge electrode, can be expressed by:

$$j = \frac{4\varepsilon_0 Z_i}{r_2^3 \ln(r_2 / r_1)} V(V - V_0) \tag{16}$$

This approximation was originally proposed by Townsend [13]. The current density in equation (16) can be expressed in term of the ion current I_{ion} toward the outer electrode wall surface area as

$$I_{\text{ion}} = \frac{8\pi\varepsilon_0 Z_i}{r_2^2 \ln(r_2 / r_1)} V(V - V_0) \tag{17}$$

Assuming that the distortion of the field distribution due to the ion space charge effect is neglected, the corona current of equation (17) is equal to

$$I_{ion} = 2\pi r_2 n e Z_i E(r) \tag{18}$$

Hence, the density is expressed by

$$n = \begin{cases} \dfrac{4\varepsilon_0}{e r_2^2}(V - V_0), & V > V_0, \\ 0, & V \le V_0, \end{cases} \tag{19}$$

It is clear that calculation of the ion current from voltage difference at the corona discharge electrode depends on the assumption of the ion properties. Although the exact physicochemical mechanism of the formation of the ions in corona discharges is not well known, there is evidence that primary ions formed in the corona region undergo a process of clustering reactions to produce ions of higher molecular weight [14]. It has been suggested that the average value for the positive and negative ion electrical mobility at atmospheric pressure were Z_i^+ = 1.4 × 10^{-4} m^2/V s and Z_i^- = 2.2 × 10^{-4} m^2/V s, respectively [15]. These are the average mobilities used throughout the calculations presented in this paper.

2.2 Estimation of the $N_i t$ Product

The particle charging performance depends on the product of the ion concentration N_i and the mean residence time t of the particles to the ions in the charger. This $N_i t$ product is the main charging parameter. Therefore, prior to any modeling of the charging process, it is necessary to estimate the $N_i t$ product established in the charging region under any operating conditions (corona voltages and sample flow rates). The ion concentration distribution is calculated by

$$N_i(r) = \frac{I_{\text{ion}}}{2\pi r L Z_i e E(r)} \tag{20}$$

The mean residence time of the particles in the charger is given by

$$t = \frac{\pi(r_2^2 - r_1^2)L}{Q_a} \tag{21}$$

where L is the length of the charging region, and Q_a is the aerosol flow rate. For the standard aerosol flow of 5.0 liter/min, the mean residence time of the particle in the charger is 0.085 s at atmospheric pressure. In calculation of variation of the particle residence time along the radial distance in the charging region, the flow velocity profile has to be taken into account. The parabolic velocity profile $u(r)$ for stationary laminar flow through the charger was assumed since the obstruction of the flow caused by the wire electrode is neglected due to the very thin ($r_1 << r_2$) wire electrode. The expression for the velocity profile is given, using "flow in a pipe" approximation, as

$$u(r) = -\frac{dp}{dz}\frac{r_2^2}{4\mu}\left(1 - \left(\frac{r}{r_2}\right)^2\right) \tag{22}$$

where μ is the viscosity of the gas, and dp/dz is the constant pressure gradient. The charging residence time with the parabolic velocity profile is given by

$$t(r) = \frac{L}{u(r)} \tag{23}$$

2.3 Estimation of the Penetration through the Charger

The particle loss inside the charger due to the electrostatic loss is defined as the ratio of the charged particles concentration at the outlet over the total concentration of uncharged particle at the inlet of the charger. The particle penetration through the charger can be calculated by Deutsch-Anderson equation as [16]

$$P = \exp\left(\frac{-2Z_p E t}{r_2}\right) \tag{24}$$

where Z_p is the electrical mobility of particle, E is the electric field, t is the mean residence time, and r_2 is the outer electrode radius. In this study, the particle loss inside the charger is primarily due to the strong electric field caused by the corona discharge. Diffusion and gravitational losses are not significant.

2.4 Estimation of the Average Charge per Particle

Upon entering a region of unipolar ions, the submicron particle will acquire some net charge within this region. The magnitude of the charge depends upon the size of the particle, the unipolar ion density encountered, and the time that particle spends within this region. In the absence of any appreciable electric field, this particle will be diffusionally charged by the Brownian random motion of the ions with respect to the particle. This diffusion charging, first characterized by White[15] and more recently modified by Pui[14], can be expressed in a convenient analytic form. For an initially neutral particle immersed in a unipolar ion cloud, the flux of ions impinging on the particle surface area is given by

$$J = 4\pi a^2 \left(\frac{N_s \bar{c}_i}{4} \right) \tag{25}$$

where a is the particle radius, N_s is the concentration of ions above the surface and $\bar{c}_i$ is the mean thermal speed of the ions. The spatial distribution of ions is given by the classical Boltzmann distribution for the equilibrium state. Neglecting the image force attraction between the ions and the particle, the Boltzmann distribution at the particle surface is given by

$$N_s = N_i \exp\left(-K_E \frac{n_p e^2}{akT} \right) \tag{26}$$

where N_i is the ion concentration at infinity, n_p is the particle charge, e is the elementary unit of charge, K_E = $1/4\pi\varepsilon_0$ with the vacuum permittivity, k is the Boltzmann's constant (1.380658 × 10^{-23} J/K), and T is the operating temperature of the system. Substituting equation (26) into equation (25) gives

$$J = \pi a^2 \bar{c}_i N_i \exp\left(-K_E \frac{n_p e^2}{akT} \right) \tag{27}$$

The above equation was originally derived by White[15]. The charging rate expression can be described by the system of differential equation as

$$\frac{dn_p}{dt} = J \tag{28}$$

With the initial condition that $n_p = 0$ at $t = 0$ for the charging of an aerosol (initially neutral), the average charge of particle can be integrated analytically to give

$$n_p = \int_0^t J dt \tag{29}$$

Thus, the average charge, n_{diff}, caused by the diffusion charging in a time period, t, by a particle diameter d_p, can be found from

$$n_{diff} = \frac{d_p kT}{2K_E e^2} \ln\left(1 + \frac{\pi K_E d_p \bar{c}_i e^2 N_i t}{2kT} \right) \tag{30}$$

where d_p is the particle diameter. The effect of the finite electric field used in the charging region can be estimated by the classical field charging equation derived by White [15], the saturation charge, n_s, of a particle (diameter, d_p and dielectric constant, ε) in an electric field E is given by

$$n_s = \left(1 + 2\frac{\varepsilon - 1}{\varepsilon + 2} \right) \left(\frac{Ed_p^2}{4K_E e} \right) \tag{31}$$

The charging rate, dn_p / dt, is

$$\frac{dn_p}{dt} = n_s K_E e Z_i N_i \left(1 - \frac{n_p}{n_s} \right)^2 \tag{32}$$

If the particle is initially neutral, the average number of charge, n_{field}, acquired in an average electric field E is given by

$$n_{field} = \left(1 + 2\frac{\varepsilon - 1}{\varepsilon + 2} \right) \left(\frac{Ed_p^2}{4K_E e} \right) \left(\frac{\pi K_E e Z_i N_i t}{1 + \pi K_E e Z_i N_i t} \right) \tag{33}$$

where ε is the particle dielectric constant. In this study, ε = 3.0 is arbitrarily assumed for the dielectric constant of the particle. Both field and diffusion charging occur at the same time. This is known as continuum charging where particle charge is the sum of the contributions from combined field and diffusion charging[17].

3. Experimental Setup

The charger in the present study is based on an electrical discharge generated between a corona-wire and an outer electrode. A schematic diagram of the unipolar corona charger is illustrated in Fig. 1. Its geometrical configuration is similar to the charger used by Lethtimaki[18] and Keskinen *et al.*[8]. It consists of a coaxial corona-wire electrode placed along the axis of a metallic cylinder(28 mm in diameter and 10 mm in length). The wire electrode is made of stainless steel, 150 μm in diameter and 10 mm long. DC high voltage is used to produce the corona discharge on the wire electrode while the outer metallic cylinder is grounded. An adjustable DC high voltage power supply (Leybold Didactic model 521721, 500 mV peak-to-peak ripple) is used to maintain this voltage difference, generally in the range between 1–25 kV. The corona discharge generates ions which move rapidly in the strong corona discharge field (>10^5V/m) toward the outer electrode wall. Aerosol flow is regulated and controlled by means of a mass flow meter and controller. The flow is directed across the corona discharge field and is charged by ion-particle collisions. This process is called diffusion charging which provides good resolution for submicron sized particles. If the ions are subjected to a strong electrical field, they will move rapidly in response to the field, greatly increasing the rate of collision between particle and ions. This is referred to as filed charging which is significant for supermicron sized particles.The performance of the charger is a function of the ion concentration in the charging zone, therefore continuous monitoring of the ion current from the corona-wire to the outer electrode is necessary. The electrometer (Keithley model 6517A) is used to measure the ion current from the corona-wire via the outer electrode. Fig. 2 shows a typical experimental setup. The current measurements are translated into ion concentrations given the mean ionic mobility and the electric field strength in the charging zone. The ionic concentration is then used as an input for the charging models.

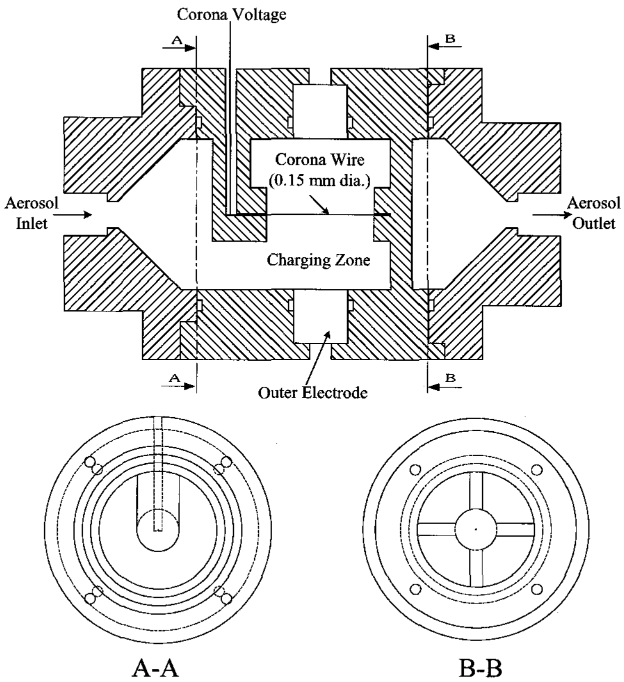

Fig. 1 Schematic diagram of the diode type corona charger

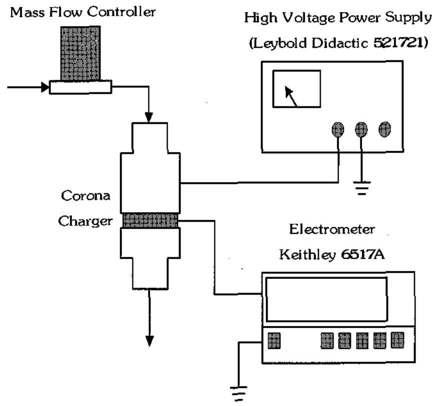

Fig. 2 Experimental setup of the ion-current measurement

4. Results and Discussion

Fig. 3 shows the relationship between ion current and the applied voltage for the charger for both positive and negative ions. Theoretical prediction was also plotted along side the ion current measurement results. Similar patterns for both positive and negative ions were produced, showing higher current for negative ions due to their higher mobility than that of positive ions. A good match of theory to the experimental curve was obtained from corona onset voltage up to about 8 kV. Large discrepancy was evident

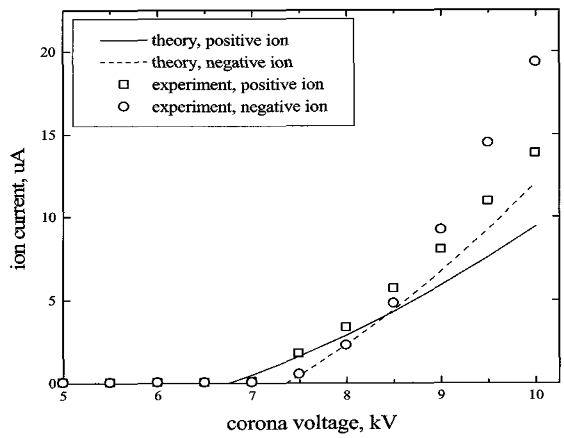

Fig. 3 Current-voltage characteristic of the positive and negative ions in the charging zone

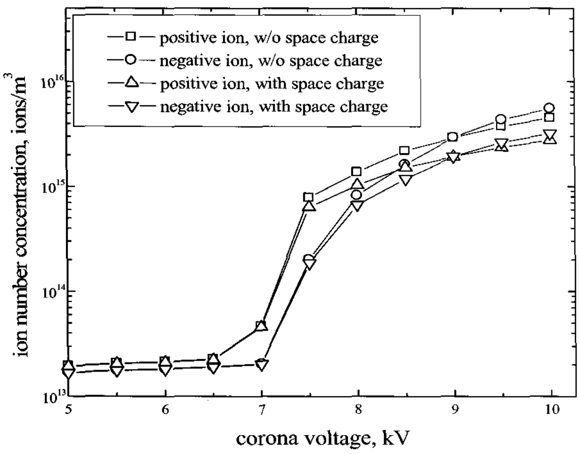

Fig. 4 Comparison of ion number concentration as a function of the corona-wire voltage

beyond this value of corona voltage where ion number concentration was high, in the region of 5 x 10^5 ions/m^3. The main reason may be explained by the fringe and the space charge effects.

The space charge effect on the ion number concentration as a function of the corona-wire applied voltage was depicted in Fig. 4. Slight differences in ion number concentration with and without considering the space charge effect were found. The difference appeared to increase with increasing applied corona voltage. Similarly, spatial distribution of electric field strength and ion number concentration was shown in Fig. 5. Increase in radial distance away from the central wire resulted in marked discrepancy in the field strength and ion concentration with and without the space charge effect. It was clear that space charge effect was significant in the corona discharge region. If the space effect was neglected, a significant error was produced. It should be noted that the influence of aerosol particles can be neglected because the particle number concentration was assumed to be much smaller than the ion number concentration.

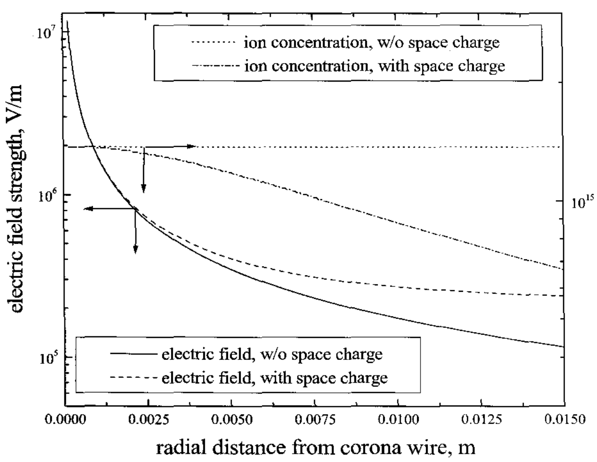

Fig. 5 Radial variation of the electric field strength and ion concentration in the charging region

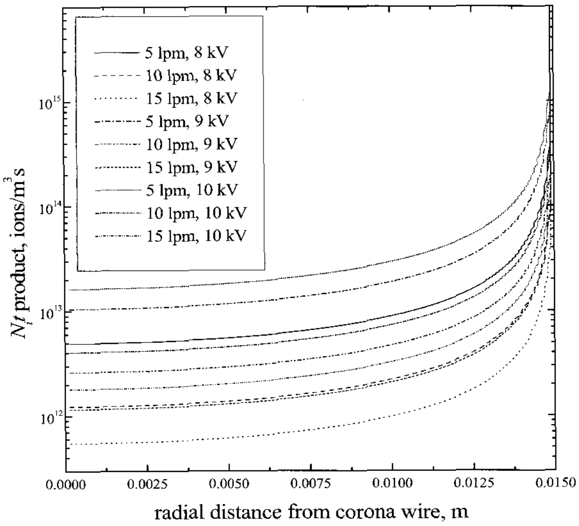

Fig. 6 Radial variation of the N_it product in the charging region at different operating aerosol rate and applied corona voltage

Particle charging depends on the product of the ion concentration and the average time the aerosol particles spend in the charger. Fig. 6 shows the radial variation of the N_it product for different operating aerosol flows and applied corona voltages. The resultant products were evaluated for 5 – 15 liter/min and 8 – 10 kV, considering the space charge effect. The obtained results were expected for the effects of aerosol flow and corona voltage. The higher flow rate, hence the shorter residence time gave rise to lower N_it product. Increase in corona voltage produced a monotonic increase in ion concentration, hence the N_it product. Overall, the N_it product did not show strong radial variation except at very close to the outer wall. The identical operating conditions were used to compute particle electrical mobility distribution and penetration

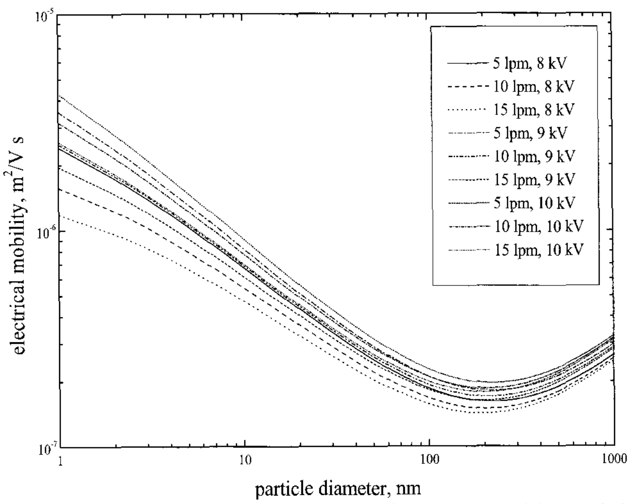

Fig. 7 Variation of particle electrical mobility with particle diameter at different operating aerosol flow rate and applied corona voltage

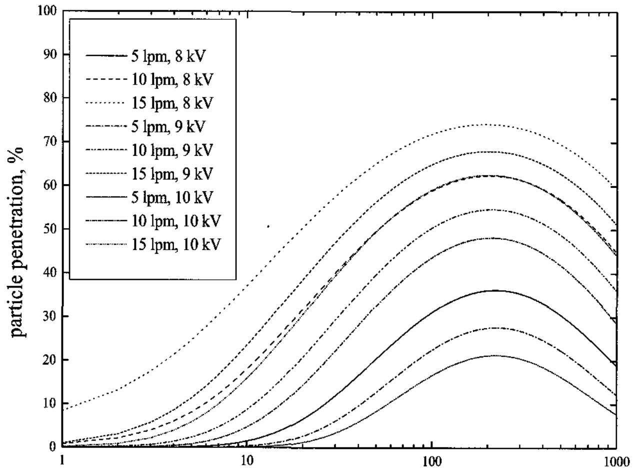

Fig. 8 Variation of particle penetration with particle diameter at different operating aerosol flow rate and applied corona voltage

through the charger as a function of particle size, shown in Figs. 7 and 8.

Long residence time and high voltage appeared to cause high level of charging, hence high electrical mobility and high deposition rate. Significant particle loss to the wall of the charger was found. Ways to overcome this high precipitation may be by (i) introduction of surrounding sheath flows at the boundary between the aerosol stream and the wall to allow more space for particle random paths, (ii) application of an AC high voltage to the electrode instead of DC voltage. The AC field was shown to produce high charging efficiencies due to lower particle losses [2, 19].

Fig. 9 shows number of elementary charge acquired versus particle size at different operating conditions. The curves were already corrected for space charge effect and particle penetration. It was clear that the number of charge increases monotonically with particle size. However, the relationship was not a linear (d) or quadratic (d^2) function of particle size as described by field and diffusion charging, respectively. In the size range considered, the combined field and diffusion charging are operating in a complicated manner. The value of charge distribution on particle is used to evaluate particle concentration and the information is useful in determining aerosol size distribution.

5. Conclusions

In this study, a diode type, wire-cylinder corona aerosol charger was built and tested. Experimental investigation of the voltage-current characteristics of the charger was compared with theoretical prediction. Results were used to characterize the electrostatic properties of the charger. A

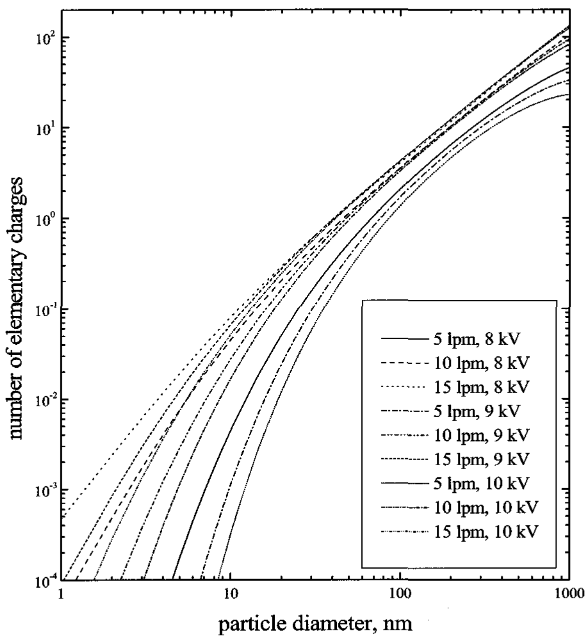

Fig. 9 Variation of number of charge with particle diameter at different operating aerosol flow rate and applied corona voltage

semi-empirical method to calculate ion concentrations in the aerosol charger based on the ion current measurements was presented. Analytical expressions were derived to yield the radial distribution of the $N_i t$ product, the corresponding particle penetration and average charge on particle of different sizes for the chosen charger geometry.

Ion number concentration and electric field strength as a function of corona voltage were evaluated. The $N_i t$ product and resulting particle size - charge distribution were presented. It was also shown that the ionic space charge has a significant influence on the electrostatic properties of the charger and particle loss due to electrostatic attraction was not negligible. The needs for surrounding sheath flows to the aerosol stream and AC high voltage supply to increase charging efficiency were also discussed. Overall, the approach proved to be useful in characterizing the electrostatic characteristics of the aerosol charger.

Acknowledgements

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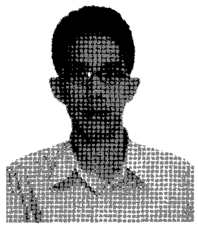

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