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Electrostatic Precipitation of Submicron Particles with an Enhanced Unipolar Pre-Charger

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ABSTRACT

A two-stage electrostatic precipitator (ESP) has been developed using an enhanced unipolar pre-charger with dielectric coated ground electrodes. The electrical and particle collection performance was evaluated for particles in the submicron range. By varying the voltage applied to the pre-charger, the particle charging characteristics was compared with that calculated by the theoretical model. The experimental results show that with the adoption of the pre-charger, the charging of the particles at submicron range was enhanced. Further results indicate that the collection efficiency can be improved by about 12.1%–15.9%, compared with the results obtained without the pre-charger. Higher particle collection efficiency can be achieved by increasing the voltage applied to the pre-charger. The unipolar pre-charger studied in this paper proves to be a simple and useful device to improve the submicron particle collection efficiency of conventional ESPs.

Keywords**:** Unipolar pre-charger; Electrostatic precipitator; Particulate matter; Corona discharge; Submicron particle.

INTRODUCTION

Particulate matter (PM) pollution has raised serious concerns globally during the past several decades. These particles can remain suspended in atmosphere, causing damages to human lungs and hearts, as well as raising environmental issues such as reduction of visibility and acting as condensation nuclei for acid rain (Kagawa and Ishizaka, 2014; Diaz-de-Mera *et al.*, 2015). In most countries, air quality legislations mandatorily regulate the concentration of PM_{10} and $PM_{2.5}$ particles to be under certain critical value. However, few legislative actions have been taken to regulate submicron particles ($PM_{1.0}$), which account for the majority of total suspended number concentration in air and are potentially more harmful for human health. Studies show that these particles can reach the systemic circulation within minutes of exposure, and subsequently have important influence on human blood system and different organs (Weichenthal, 2012).

Electrostatic precipitators (ESPs) are commonly used in both industrial and household applications to remove suspended fine particles. The advantages of ESPs include high mass collection efficiency, low pressure drop, and high operating flow rate (Jaworek *et al.*, 2007). However, conventional ESPs suffer the low collection efficiency at submicron range, because of the low charging rate and low migration velocity of these particles. The minimum collection efficiency is usually observed in the 0.1–1 µm range, due to the fact that it is relatively difficult to charge them with more than a few elementary charges (Le *et al.*, 2013). Different methods have been developed to mitigate this problem. Nucleated or heterogeneous condensation, in which water vapor was mixed in exhaust gas, was applied to enhance the agglomeration of submicron particles (Huang *et al.*, 2007; Chen *et al.*, 2014). An increase of collection efficiency of 40%–80% was observed for particles from 50–100 nm. The efficiency was further increased to 80%–90% for particles larger than 100 nm (Tsai *et al.*, 2005). Electric agglomeration was proposed by different groups to increase the electrostatic attraction among particles to enhance the collection efficiency by using bipolar pre-chargers (Kanazawa *et al.*, 1993; Zhu *et al.*, 2010; Chang *et al.*, 2015). Particles charged with different polarities can attach to each other and form larger ones, so that they can be more easily removed. Grade collection efficiency as high as 98% was achieved by using a closed-loop bipolar pre-charger (Zhu *et al.*, 2010). Attempts have also been made to enhance the charging of the fine particles using various charging techniques such as UV irradiation (Jung *et al.*, 1988) and soft X-rays (Jung *et al.*, 1988; Kulkarni *et al.*, 2002). Noorpoor

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(2012) demonstrated the feasibility to increase particle vibration and agglomeration using acoustic waves. Other techniques utilized to improve collection efficiency for submicron particles include bag filters, cyclones, and scrubbers (Lin *et al.*, 2008; Zarei *et al.*, 2010).

In a conventional ESP, particles are charged by corona discharge generated at the high voltage electrode. From the theoretical side, the Deutsch model is a widely accepted model to calculate the collection efficiency of dry ESPs. The Deutsch formula can be written as follows (Matts and Ohnfeldt, 1963):

$$\eta = 1 - \exp\left(-\frac{v_m A}{V}\right) \tag{1}$$

where v_m is the mean migration velocity of the particle, A is the cross-section area of the precipitator, and V is the gas flow rate. From the above formula, it can be seen that at a given flow rate and cross-section area, one can increase the collection efficiency by increasing particle migration velocity, which is proportional to the charge on each particle.

The total number of elemental charges on a particle can be expressed as:

$$n_p = n_{diff} + n_{field} \tag{2}$$

where n_p is the total number of charges on the particle, n_{field} is the field charging term, which arises from the deposition of ions onto the particle due to electrostatic force caused by the collection electric field, and n_{diff} is the diffusion charging term, which arises from the bombardment of particle by kinetic movement of gaseous ions independent of the collection electric field. Use Fuchs equation for diffusion charging (Fuchs, 1947), and Pauthenier and Moreau-Hanot equation for field charging (Pauthenier and Moreau-Hanot, 1932):

$$n_{diff} = \frac{dkT}{2K_E e^2} \ln\left(1 + \frac{\pi K_E d v_g e^2 N_i t}{2kT}\right) \tag{3}$$

$$n_{field} = \frac{3\epsilon_r}{\epsilon_r + 2} \frac{E_{ave} d^2}{4K_E e} \left(\frac{\pi K_E e Z_i N_i t}{1 + \pi K_E e Z_i N_i t}\right) \tag{4}$$

where d is diameter of the particle, k is the Boltzmann constant (1.38×10^{-23} J K^{-1}), T is the temperature, $K_E = 9.0 \times 10^9$ Nm C^{-2}, e is the elementary charge (1.6×10^{-19} C), v_g is the mean thermal velocity of ions, N_i is the average ion concentration, t is the residence time of particles in the charging zone, ε_r is the relative electrical permittivity of particles, E_{ave} is the average electric field strength, and Z_i is the ion mobility. For both charging mechanism, it is obvious that the charging rate increases with the product of ion concentration and residence time, $N_i t$. Generally, the residence time of particles is limited. Longer residence time usually means lower gas velocity and lower flow rate, which is not desirable for both industrial and household applications. So one cannot increase the residence time without sacrificing the total flow rate too much. Alternatively, if higher space ion concentration could be generated inside the charging zone, one can anticipate to effectively charge the particle with higher number of elementary charges. The ion concentration is generally decided by the generation and loss of ions in the charging zone. If one can manage to increase the discharge current while limit the ion dissipation rate, the collection efficiency would be significantly increased.

In this study, a simple but effective unipolar pre-charger with enhanced charge production has been designed and constructed. By coating the ground electrode with dielectric layer and thus preventing the dissipation of negative ions into the ground, we demonstrate that we are able to significantly increase the ion concentration in the pre-charger and subsequently enhance the charging of the particles at submicron range. Further results indicated that the collection efficiency can be improved by about 12.1%–15.9%, compared with the results obtained without the pre-charger. Also the collection efficiency is comparable with bipolar pre-chargers with relatively more complicated designs. To get deep insights into the effects of the pre-charger on ESP performance, the charging characteristics and submicron particle collection efficiency are investigated at different operating conditions. The results are compared with the cases without the pre-charger, to assess the improvement on the submicron particle removal performance.

EXPERIMENTAL SETUP

Fig. 1 shows the schematic diagram of the experimental setup. The system consists of an enhanced unipolar pre-charger, a conventional ESP, power supplies, a particle generator and an aerosol size distribution measurement system. When the particles go through the system, they are charged in the pre-charger, and collected by the ESP.

The pre-charger is placed in front of the ESP. The width, height and length is 15 cm, 10 cm, and 20 cm, respectively. The pre-charger consists of two sets of electrodes, as shown in Fig. 2. Each set consists of 5 high voltage electrodes and 4 ground electrodes placed in parallel position. All the electrodes are wire-type with a diameter of 0.5 mm. The high voltage electrodes are connected to a negative DC power supply. The ground electrodes are coated with a 1 mm thick dielectric layer. The distance between the high voltage electrodes and ground electrodes is 10 mm. The flow velocity is controlled at 1.0 m s^{-1} to ensure sufficient charging time and minimal particle collection in the pre-charger.

The particles are charged in the pre-charger, and collected in the ESP. The ESP is a single stage wire-plate type. The width, height and length is 30 cm, 20 cm, and 60 cm, respectively. The distance between the wire and the plate is 10 cm. The flow velocity inside the ESP is 0.25 m s^{-1}, and the particle residence time is 2.4 s. Voltage and current waveforms of the pre-charger and ESP are recorded with a Tektronix MDO3104 oscilloscope.

Commercial nano-sized Calcium carbonate is used as the particle source (American Elements, 97.5% purity). A vertical particle injector, which uses the pressure drop in

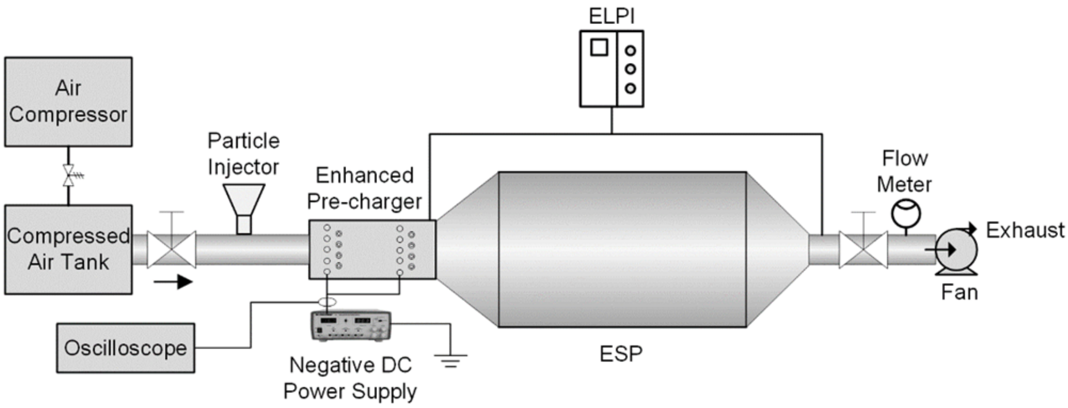

Fig. 1. Schematic diagram of the experimental setup.

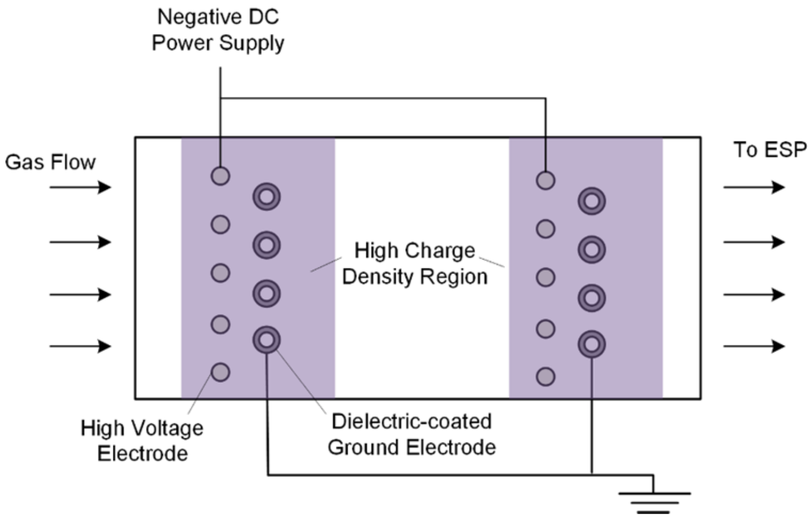

Fig. 2. Schematic diagram of the unipolar pre-charger.

the air flow across an orifice plate in the circular pipe, is employed to entrain the particles. The opening of the orifice can be adjusted to allow control of the mass concentration of injected particles. An electrical low pressure impactor (ELPI) is installed at the downstream of the pre-charger and ESP for in-situ diagnostics of particle size and charge unit distribution. The measurement size range is 30 nm to 10 µm. The particle number concentration is sampled by an isokinetic sampling probe from Dekati. The sampling flow rate of the ELPI is 10 L min^{-1}. The typical particle size distribution is shown in Fig. 3. The inlet mass concentration is controlled at about 1.5 mg m^{-3} to simulate the seasonal spike of smog concentration in China, which may exceed 1000 µg m^{-3} during winter. All experiments are conducted at room temperature, which ranges from 15°C to 25°C. The humidity is maintained at 60% ± 5%. The operating pressure is maintained at atmospheric pressure.

RESULTS AND DISCUSSION

Voltage-Current Characteristics

Fig. 4 shows the voltage-current (V-I) characteristics curve of the pre-charger and the ESP. The negative corona starts at the voltage of 4.5 kV in the pre-charger. For the ESP, the negative corona starts at the voltage of 8 kV. Corona discharge current increases with applied voltage. Because

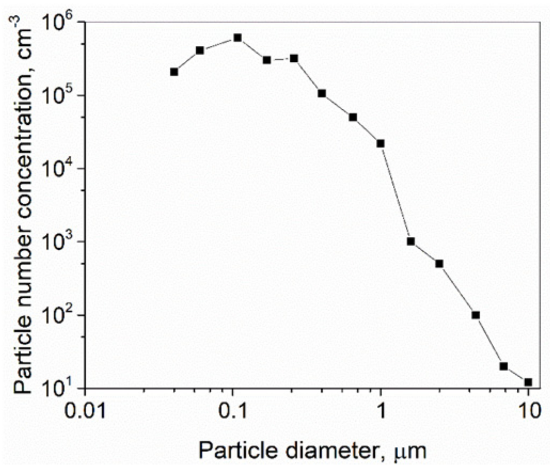

Fig. 3. Typical particle number distribution at the inlet with a mass concentration of 1.5 mg m^{-3} and a flow velocity of 1.0 m s^{-1}.

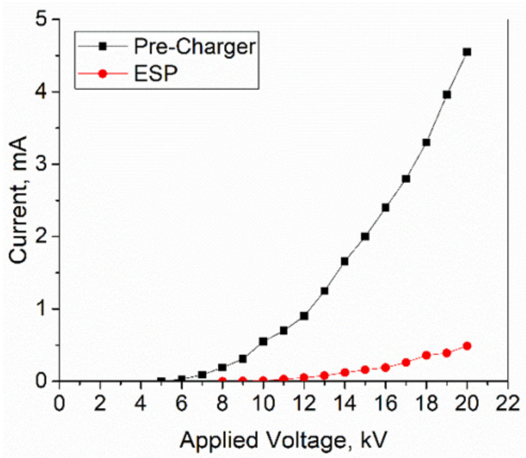

Fig. 4. Voltage-current characteristics of the pre-charger and the ESP.

of the much shorter distance between the high voltage electrode and the ground electrode, and consequently higher electric field, the negative corona current in the pre-charger is much higher than that of the ESP. The negative ions are transported from the high voltage electrodes towards the grounded electrodes. However, the presence of the dielectric layer on the ground electrodes prevents the dissipation of negative ions into the ground. Part of the negative ions are deposited on the dielectric layer, which produces extra electric field and prevents further deposition of the charges onto the dielectric layer. As a result, a high charge density region is formed in the space close to electrodes. When the particles pass through the pre-charger, they experience a much higher charge density and are charged with higher number of elementary charges. This is confirmed by the charging characteristics measured by the ELPI, which will be described in the next section. The dielectric layer at the ground electrodes also act as barrier to prevent the formation of spark so that higher voltage can be applied.

Charging Characteristics

As mentioned previously, the charge concentration N_i is the key to enhance the charging of the particles. It can be calculated as (Kirsch and Zagnit'Ko, 1981):

$$N_i = \frac{J_p}{Z_i E_{ave} e} \tag{5}$$

J_p is the average current density, and is defined as:

$$J_p = \frac{I}{4 S_x l} \tag{6}$$

where I is the total ion current per discharge wire, S_x is the distance of discharge wire to wire, and l is the wire length.

The average electric field strength E_{ave} is calculated as:

$$E_{ave} = \frac{\pi r_c E_c}{2 S_x} \tag{7}$$

where r_c is the radius of the discharge wire, and E_c is the corona initiating electric field. For simplification, E_c is assumed to be 3×10^6 V m^{-1} without considering the roughness factor of the wire surface. The total ion current I can be calculated by the procedure presented by Lin et al (Lin *et al.*, 2012). Table 1 shows the estimated charge concentration calculated in the pre-charger and ESP using the measured corona current. The negative ion mobility is set to be 1.57×10^{-4} m^2 Vs^{-1} (Lin *et al.*, 2012). It can be seen that given the same applied voltage, the charge concentration in the pre-charger is generally 1.5 orders of magnitude higher than that in the ESP, which may provide efficient charging for submicron particles.

Solving Eqs. (2)–(5) simultaneously can give the theoretical number of elemental charges on particles due to diffusion and field charging. In the meanwhile, from the experimental side, assuming that for the particles with same size, the amount of charges attached on them is the same, the equation for calculating the number of charges collected by the particles can be expressed as:

$$\mathrm{n} = \frac{I}{Q \times N \times e} \tag{8}$$

where n is average number of elementary charges on particle, I is the diagnostic current of ELPI (A), Q is the sample flow rate (cm^3 s^{-1}), N is the number concentration of particles (cm^{-3}). Using the above equation, the characteristics of average particle charge are investigated by the ELPI diagnostic data. Fig. 5 shows the typical charging characteristics of the particles at applied voltage of 10 kV on the pre-charger, and its comparison with theoretical results obtained by solving Eqs. (2)–(5). The experimental data is measured immediately after the pre-charger. Reasonably good agreement is obtained for particles in the submicron range, although experimental results are consistently lower than the numerically predicted results. This is probably due to the fact in the theoretical model, the residence time is calculated using the length of the pre-charger, divided by the gas flow velocity. But in reality, the width of the high charge density region is much shorter than the length of the pre-charger, leading to much shorter residence time. It is also shown that for particles with diameter larger than 300 nm, field charging is the major charging mechanism, while for particles smaller than 300 nm, diffusion charging plays the

Table 1. Estimated charge concentration calculated in the pre-charger and ESP using the measured corona current.

	Pre-charger			ESP		
Voltage	10 kV	15 kV	20 kV	10 kV	15 kV	20 kV
Charge concentration, m^{-3}	2.5×10^{14}	6.1×10^{14}	9.1×10^{14}	3.5×10^{12}	1.3×10^{13}	3.1×10^{13}

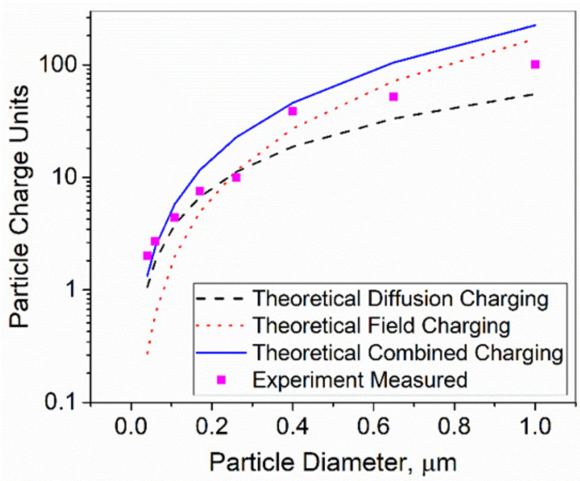

Fig. 5. Comparison of theoretical and experimental particle charging characteristics of the pre-charger with applied voltage of 10 kV.

dominant role. In our interested range of 50 to 1000 nm, both field and diffusion charging decrease with the particle size. Therefore, minimum collection efficiency is usually observed for conventional ESPs in this size range.

Fig. 6 shows the typical charging characteristics of the particles with different voltage applied on the pre-charger. Generally, the number of charges rises with the increasing of the applied voltage. For all cases, the particle charge unit value with the pre-charger switched on is increased by over five times, comparing with the case where the pre-charger is switched off (applied voltage = 0). It has to be noted that for case A, B and C, the results are measured directly after the pre-charger. For case D, in which the pre-charger is switched off, the results are measured at the outlet of the ESP. Hence the comparison here only provides qualitative information.

Collection Efficiency

The collection efficiency is calculated according to the concentration at the inlet and outlet, using the following equation:

$$\eta = \frac{N_{inlet} - N_{outlet}}{N_{inlet}} \tag{9}$$

where η is the grade collection efficiency, N_{inlet} is the number concentration (cm^{-3}) at the inlet, and N_{outlet} is the number concentration (cm^{-3}) at the outlet.

Fig. 7 shows the typical collection efficiency of the ESP at different operation voltage when the pre-charger is switched off. The voltage of the ESP varies from 10 kV to 20 kV. Results show that the collection efficiency increases with the rise of the ESP operation voltage. The collection efficiency curve is U-shaped, and minimum efficiency is observed at the diameter range of 0.1–0.5 µm. This is consistent with previous research, which attributed the low efficiency to balance between decreasing charge with decreasing particle size and increasing drag with increasing particle size (Kulkarni *et al.*, 2002). At discharging voltage of 20 kV, the total collection efficiency is 80.3%.

Fig. 8 shows the grade collection efficiency when the pre-charger is switched on. The operation voltage of the ESP is fixed at 20 kV. The voltage of the pre-charger is varied from 10 kV to 20 kV. Note that the wall loss of the particles in the unipolar pre-charger is about 4% to 6% at different applied voltages. Generally, the enhanced charging effect of the pre-charger can improve the collection efficiency by 12.1%–15.9%. For particles with diameter range of 0.1–0.5 µm, the improvement is especially obvious. Fig. 8 also shows the effect of negative corona intensity by changing the voltage on the pre-charger. The total collection efficiency is increased from 92.4% to 96.2%, when the voltage is

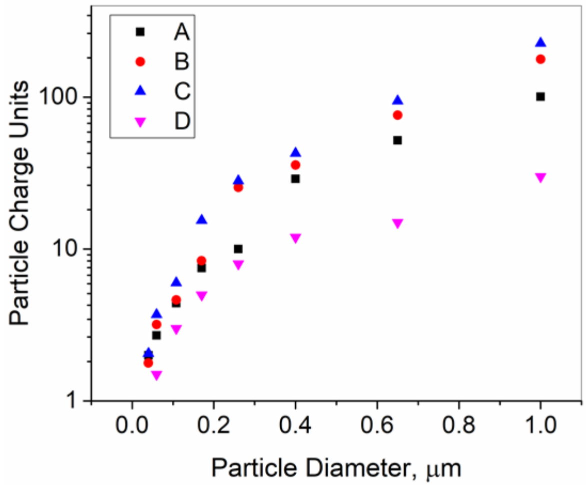

Fig. 6. Charging characteristics for particles with different diameters. For case A, B and C, the pre-charger is switched on, the voltage is 10 kV, 15 kV and 20 kV, respectively. The results are measured directly after the pre-charger. For case D, the pre-charger is switched off, and the results are measured at the outlet of the ESP.

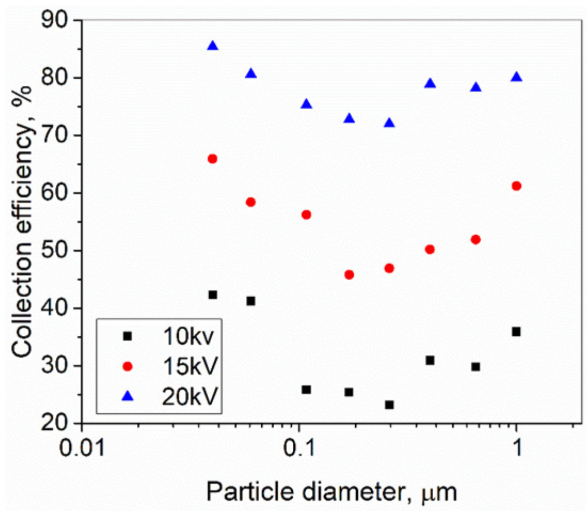

Fig. 7. Grade collection efficiency of the ESP with the pre-charger switched off. The voltage of the ESP is varied from 10 kV to 20 kV.

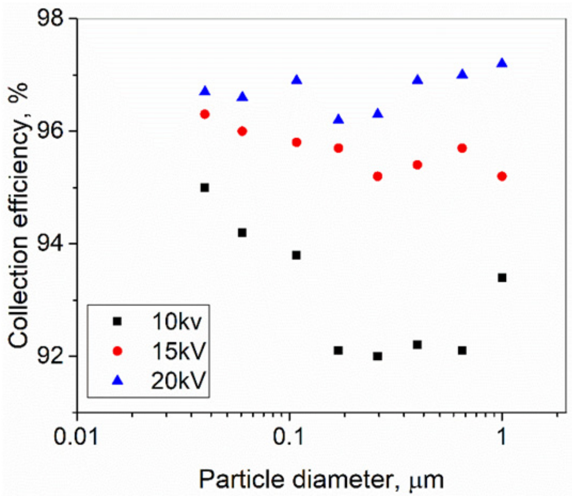

Fig. 8. Grade collection efficiency with the pre-charger switched on. The voltage of the ESP is fixed at 20 kV. The voltage of the pre-charger is varied from 10 kV to 20 kV.

raised from 10 kV to 20 kV. This value is close to the collection efficiency obtained with the bipolar pre-charger (Chang *et al.*, 2015). Current results clearly indicate the effectiveness of the pre-charger as charging the particles is enhanced in the high charge density region. Another effect worth noting is the ionic wind produced in the high charge density region. The ionic wind can produce strong turbulence, improve particle mixing and potentially enhance the charging process.

CONCLUSIONS

This study designed and developed a simple unipolar corona pre-charger with dielectric coated ground electrodes to improve the submicron particle removal performance. Experiments were conducted to investigate the charging and collection efficiency of submicron particles. It was demonstrated that by preventing the dissipation of negative ions into the ground electrode, the ion concentration was increased and subsequently charging of the particles at submicron range was enhanced. Further results indicated that the collection efficiency can be improved by about 12.1%–15.9%, compared with the results obtained without the pre-charger. Also the collection efficiency is comparable with bipolar pre-chargers with relatively more complicated designs. Overall, the unipolar pre-charger studied in this paper proves to be a useful device to improve the submicron particle collection efficiency of conventional ESPs. For optimization purposes, future works will be focused on the study of the influence of particle size, gas velocity, voltage magnitude and polarity on the charge enhancing effect.

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