Quantifying the Effect of Nonwoven Conductive Fabric Liners on Electrostatic Precipitator Submicrometer Particle Removal Efficiency

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ABSTRACT

Electrostatic precipitators (ESP) are widely used for fine particle control. The collection surface is sometimes coated with materials to enhance pollutant removal. The use of nonwoven fabric liner inserts for submicrometer particle removal in an ESP was investigated. Two of the nonwoven fabrics (HAS-10(S)F1SS/PML and HPS-10(S)FIL/F1SS/BSL) were conductive, whereas the third one (RR-10(S)F1SS/DSL) was non-conductive. The current-voltage characteristics of the ESP revealed lower inception voltages when conductive fabrics were used (5.0 kV for HAS-10(S)F1SS/PML and 6.1 kV for HPS-10(S)FIL/F1SS/BSL) than when no fabric was used (6.9 kV), whereas no distinct inception voltage was observed with the non-conductive fabric due to it possessing lower concentrations of reactive electrons and ions on the surface compared to the conductive fabrics. The particle capture performance of the ESP with and without nonwoven fabrics was studied using NaCl particles at applied voltages ranging from 0 kV to 7.5 kV. Due to their lower inception voltages and higher ion concentrations, the conductive fabrics exhibited higher particle removal efficiencies than the other test cases when the applied voltages were lower than 7.5 kV. High removal efficiencies were still obtained at an applied voltage of 7.5 kV except when the particles were smaller than 30 nm or larger than 700 nm due to the lower charging efficiency with ultrafine particles and the re-entrainment of larger particles. However, the use of either conductive or non-conductive fabric resulted in a higher charging efficiency with ultrafine particles and the reduced re-entrainment of large particles. Our findings elucidate the enhancement of submicrometer particle control in ESPs when using conductive fabrics.

Keywords: Fabric conductivity; Current-voltage characteristics; Ion concentration; Particle charging; Re-entrainment.

INTRODUCTION

Airborne submicrometer particles have long atmospheric residence times and pose severe health risks. Increasingly stringent international emissions regulations and air quality standards have heightened the need for innovative solutions (Morawska et al., 1998; Chan et al., 2004; Li et al., 2016). Commonly used methods of particle removal include fabric filtration, combined gravitational and centrifugal separation, wet scrubbing, and electrostatic precipitation. Fabric filtration and electrostatic precipitation are the best available technologies for particle removal (Capocelli, 2015). Gravity separation is less favored for submicrometer particle removal because it often requires high maintenance, has long cleaning times, and is poor at separating fine particles (Falconer, 2003).

Wet scrubbers have limitations in separating gaseous flow effluents, because they require a high pressure drop for efficiency and have limited operating flow rates and temperatures, compared to other methods of particle removal (Mussatti, 2002). Electrostatic precipitators (ESPs) are widely used for particle removal in many large industrial operations, such as coal power plants. ESPs clean effluent gas emissions from particle-heavy processes before they enter the atmosphere. Their low cost of removal, high removal efficiencies, and wide range of operating conditions, from ambient to high temperature, make them favorites in industrial application (Kulkarni et al., 2002; Durme et al., 2008; Li et al., 2016).

ESPs are highly effective at removing particulate from effluent gas waste streams, but cleaning them is time-consuming and exposes workers to toxic chemicals (Austin, 1999). In the case of dry ESPs, they can be partially cleaned via mechanical rapping, but additional cleaning and inspection are typically needed to maintain particle removal efficiencies (Austin, 1999; Adabara, 2017). ESPs can also be cleaned via intermittent water jet washes, but this method limits the operating time of the ESP, which must be de-energized during cleaning (Seetharama et al., 2013). Because ESPs remove
particles, they are inherently messy to clean, and it is easy for the captured particles to dislodge during cleaning. If loose particles are inhaled, they cause myriad health problems, such as asthma and other respiratory or irritation-related disorders (Ardkapan, 2013; Adabara, 2017). In the case of wet ESPs, they have no issues related to trapping re-entrainment but the collected slurry on the collectors requires more careful treatment, which can increase the expense of the cleaning (U.S. EPA, 2002).

Additionally, the ESP corona on its own is inadequate to efficiently remove submicrometer particles (Kulkarni et al., 2002; Li et al., 2016). The overall removal efficiency of particles with the ESP is approximately 99% based on mass. However, the collection efficiency of particles with the ESP was decreased within the submicrometer size range (70–80%) due to the lower charging efficiency with decreasing particle size (Kulkarni et al., 2002). Therefore, a complementary technology or improvement could enhance removal efficiencies at submicrometer sizes (Kulkarni et al., 2002). Such methods include coating the ESP in titanium dioxide photocatalyst, pulsing high voltages across the ESP, and using soft X-rays to effectively charge and remove submicrometer particle by generating more ions inside the ESP (Kibanova et al., 2009; Grigoriu et al., 2012; Kettleson et al., 2013).

Recently, nonwoven fabrics have attracted interest for their unique compositions and durability, and have many applications, from cleaning products to durable flooring in cars (Kuhn et al., 1993; Stefecka et al., 2004; Yamashita et al., 2013). However, there is little literature on nonwoven fabric liner inserts for ESPs. The collected particles on the outer electrode inside the ESP could be re-entrained into the gas stream, which might be due to the electrode surface structure, gas velocity, particle size, and ionic wind (Zukeran et al., 1999; Sung et al., 2006). The previous study by Sung et al. (2006) utilized fibrous implementations inside ESPs and reported improved ESP particle removal efficiencies by inhibiting the re-entrainment via the charged structure of the electrode surface with fibers. Even though it has the mechanical advantage for particle removal, a major concern with implementing fabrics inside ESPs is still that their non-conductive nature might not allow for a stable voltage gradient to be established between the electrodes, hindering corona generation.

Electroconductive nonwoven fabrics have recently become industrially available and are made by incorporating conductive materials or atypical structures into the nonwoven fabric during production (Maity and Chatterjee, 2015). The incorporation of electroconductive nonwoven material, depending on the material’s resistivity, could both maintain the ESP’s particle removal via corona-related effects and reduce re-entrainment effects. In addition, a removable electroconductive liner could reduce hazardous maintenance and cut operational costs.

In this study, the effect of conductive and non-conductive fabrics on the corona generation and particle removal in an ESP was examined. To investigate their feasibility as an ESP liner, the morphology, chemical composition, and resistivity of three fabrics of interest were assessed. Current-voltage characteristics of the ESP with and without nonwoven fabrics were investigated. The particle removal efficiencies of the ESP with and without nonwoven fabrics were determined by comparing the initial and post-process particle counts.

**EXPERIMENTAL**

**Fabric Evaluation**

Three fabrics (HAS-10(S)F1SS/PML, HPS-10(S)FIL/F1SS/BSL, and RR-10(S)F1SS/DSL) were provided via Supreme Nonwoven Industries. The morphologies and elemental compositions of the three fabrics were evaluated by field emission scanning electron microscopy (FE-SEM; Nova NanoSEM 230; FEI) and energy-dispersive X-ray (EDX) spectroscopy.

The resistances of the fabrics were determined by a resistivity test cell (Models 828M and 871; ETS). The cells were first calibrated using different resistors, then the fabrics were cut into 25 cm² circles to be inserted into the resistivity test cell. The inserted fabrics were properly contacted with the electrodes, and a connected resistance meter read the resistance ($R$, $\Omega$) of each material. The resistivity ($\rho$, $\Omega \cdot m$) was calculated by:

$$\rho = \frac{A}{lt},$$

where $A$ and $t$ represent the cross-sectional area (25 cm²) and the thickness of each fabric, respectively.

**Experimental Setup and Procedure**

The experimental setup is depicted in Fig. 1. A direct current (DC) corona-based wire-cylinder ESP was used, which consists of a PVC shell, a cylindrical collecting electrode (stainless steel, 25.4 cm in length and 4.8 cm in diameter), a centered wire discharge electrode (stainless steel, 0.323 mm in diameter), and insulating caps at the top and bottom of the ESP to house the ends of the discharge electrode. A Bertan power supply (Model 205B-20R; Spellman, Hauppauge, NY, USA) was used to increase and adjust the operating voltage of the ESP. To produce large numbers of charge carriers in the gas phase, an electrical field has to be induced via a high voltage (Parker, 1997; Li et al., 2016). An atomizer (Model 3076; TSI Inc., Shoreview, MN, USA) was used with a 0.2 M NaCl solution to generate polydisperse aerosolized NaCl droplets. A cylindrical silica gel diffusion dryer was used to remove water vapor from the generated NaCl droplets, because humidity has been shown to affect the removal efficiency of ESP devices by disrupting the mean free path and generation of radicals (Kulkarni et al., 2002; Durme et al., 2008). A $^{210}\text{Po}$ radiation source neutralizer was used to make the generated submicrometer particles carry a zero or a low number of charges (Li et al., 2016). The particles were then introduced into the ESP and the flow rate was fixed at 1.5 L min$^{-1}$ (residence time: ~18 s). A scanning mobility particle sizer (SMPS Model 3081; TSI Inc., Shoreview, MN, USA) was used to measure the particle size distribution of the aerosolized NaCl stream leaving the ESP.
ESP particle removal experiments were conducted with negative polarity, which, compared to positive polarity, generates a more stable negative corona at a lower inception voltage (Parker, 1997; Kulkarni et al., 2002; Durme et al., 2008; Patino et al., 2016). Three fabrics were cut to fit as a liner within the circumference of the ESP, which was calculated to be approximately 150.8 mm, so the fabrics were cut into strips with a width of 135 mm to account for their thickness and correspondingly smaller circumferences. Then, the fabrics were inserted into the ESP and placed on the collecting electrode (Fig. 1). The experimental setup was operated at ambient temperature and pressure conditions.

Different experiments were conducted to investigate the effect of conductive and non-conductive fabrics on particle removal in the ESP (Table 1). First, the control current-voltage (I–V) characteristics and ion production without fabric under various DC voltages were studied (Set I). Next, the I–V characteristics and ion production with different fabrics (conductive and non-conductive) were investigated (Set II), and the results were compared with those obtained from Set I. Third, particle removal tests without fabric were conducted under various DC voltages (Set III). Finally, particle removal tests with different fabrics (conductive and non-conductive) were performed (Set IV), and the results were compared with those obtained in Set III. The experiments were performed in triplicate to ensure repeatability.

RESULTS AND DISCUSSION

Fabric Morphology, Composition, and Resistivity

The surface morphologies and compositions of three different fabrics were investigated by using FE-SEM and the results are shown in Fig. 2. As can be seen in Fig. 2, all three fabrics showed a similar random distribution of fibers in their nonwoven structure. The thickness of most fibers in all the fabrics was approximately 10 µm. The chemical compositions on the surfaces of all three fabrics were confirmed by using EDX spectroscopy, and the results are shown in Fig. 2. The spectra of two fabrics (HAS-10(S)F1SS/PML and HPS-10(S)FIL/F1SS/BSL) showed similar chemical composition on their surfaces (~75% carbon and ~25% oxygen). On the other hand, RR-10(S)F1SS/DSL showed a different spectrum in which 75.5% carbon, 2.2% oxygen, 3.4% iron and 18.9% sulfur were detected. Previous studies reported the different surface resistivities by changing the chemical compositions on the fabrics’ surfaces (Kalanyan et al., 2013; Stoppa and Chiolerio, 2014; Kongahage et al., 2016). Kongahage et al. (2016) synthesized graphene-coated nonwoven fabrics and observed the decreasing surface resistivity as the mass of carbon on the fabric’s surface increased. Other studies also obtained the lower surface resistivity by coating metals on the fabrics’ surfaces (Kalanyan et al., 2013; Stoppa and Chiolerio, 2014). These previous studies indicate that the electric properties of nonwoven fabrics are significantly affected by the chemical compositions on their surfaces. Therefore, the observed different chemical compositions on the three fabrics’ surfaces might result in different electric properties. The resistivities of the three fabrics were investigated and the test results are shown in Table 2. HAS-10(S)F1SS/PML showed the lowest resistivity (93.2 Ω m), followed by HPS-10(S)FIL/F1SS/BSL (219.0 Ω m) and RR-10(S)F1SS/DSL (3.44 × 10^{12} Ω m). The extremely high resistivity of RR-10(S)F1SS/DSL might be due to its chemical composition (Fig. 2). Sulfur is known to have a very high resistivity (1 × 10^{15} Ω m), which might result in the extremely high resistivity of RR-10(S)F1SS/DSL. Compared to previously
### Table 1. Summary of performed studies.

| Set | Description | Voltage (kV) | Fabrics used | Objectives |
|-----|-------------|--------------|--------------|------------|
| I   | I–V characteristics and ion production of the ESP + Air | 5–8 | N/A | • Obtain control I–V curve results for ESP + Air  
• Study the inception voltage and ion production |
| II  | I–V characteristics and ion production of the ESP + non-conductive fabrics | 5–8 | 2 conductive + 1 non-conductive | • Obtain I–V curve results for ESP + conductive or non-conductive fabrics  
• Study the inception voltage and ion production |
| III | Particle removal efficiency of ESP + Air | 0–7.5 | N/A | • Obtain particle size distribution for ESP + Air at varied ESP operational voltages |
| IV  | Particle removal efficiency of ESP + non-conductive fabric | 0–7.5 | 2 conductive + 1 non-conductive | • Obtain particle size distribution for ESP + conductive or non-conductive fabric at varied ESP operational voltages |

**Fig. 2.** SEM images and EDX spectra of (a) HAS-10(S)F1SS/PML, (b) HPS-10(S)F1SS/BSL, and (c) RR-10(S)F1SS/DSL.

### Table 2. Thicknesses and resistivities of fabrics.

| Fabric product code | Thickness (mm) | Resistivity (Ω m) |
|---------------------|----------------|-------------------|
| HAS-10(S)F1SS/PML   | 2.2            | 93.2              |
| HPS-10(S)F1SS/BSL   | 2.1            | 219.0             |
| RR-10(S)F1SS/DSL    | 2.0            | $3.44 \times 10^{12}$ |
reported resistivities of active carbon nonwoven fabrics (< 10 Ω m) (Cislo et al., 2004), HAS-10(S)F1SS/PML and HPS-10(S)FIL/F1SS/BSL have resistivities that are higher by one order of magnitude. However, their resistivities were much lower than that of RR-10(S)F1SS/DSL, and therefore they were considered as the conductive fabrics in this study, while RR-10(S)F1SS/DSL was selected as the non-conductive fabric.

**Current-voltage (I–V) Characteristics and Ion Generation**

The current-voltage (I–V) characterization was performed with two conductive fabrics (HAS-10(S)F1SS/PML and HPS-10(S)FIL/F1SS/BSL), a non-conductive fabric (RR-10(S)F1SS/DSL), and no fabric, at voltages ranging from 5.0 kV to 8.0 kV, with the results depicted in Fig. 3(a). In all cases except for the non-conductive fabric, an increasing current was observed after a certain voltage, called the negative corona inception voltage, showing the existence of negative corona discharge. HAS-10(S)F1SS/PML fabric showed the lowest inception voltage (~5.0 kV), followed by HPS-10(S)FIL/F1SS/BSL (~6.1 kV), and then without fabric (~6.9 kV). RR-10(S)F1SS/DSL did not show the noticeable inception voltage. When an ESP is operating, the negative corona generates excessive negative ions in the gas phase (Kulkarni et al., 2002). In this condition, particles undergo diffusion charging, in which ionized gas molecules are attached to the particles to form negatively charged particles (Kulkarni et al., 2002). These charged particles move and are deposited on the ESP’s outer electrode. In cases using conductive fabric liners, more active electrons are expected to be generated on the surface of the fabrics due to their conductive properties, resulting in greater ionization of gas molecules near the surface of the fabrics. Therefore, both a lower inception voltage and higher current can be expected when the ESP setup is altered using conductive fabrics. On the other hand, when non-conductive fabric liner is incorporated, no noticeable current increase was observed due to its non-conductive characteristic. It is also worth noting that the lower inception voltage and the higher current at any applied voltages lower than 7.8 kV were observed in the cases using conductive fabrics compared to the case without fabrics. The electrode was originally made of stainless steel and thereby the lower resistivity (6.9 × 10⁻⁷ Ω m) is expected. The observed finding of the lower inception voltage and the higher current with the conductive fabrics might be explained by the generation of more active electrons on the surfaces of the conductive fabrics compared to the original electrode. The generation of active electrons on the surface of the material depends on its work function which is the required energy to extract an electron from the material’s surface. Previously, the reduced work function with oxygen-added carbon compared to the original carbon was reported (Zheng et al., 2003), which could be competitive or lower than the work function of stainless steel (~4.4 eV). The I–V characteristics reflect this explanation (Fig. 3(a)).

Based on the determined I–V characteristics, the following equation was used to calculate the ion concentrations \(N_i\) (# cm⁻³) in the ESP setup with conductive fabrics, with non-conductive fabric, and with no fabric (Kirsch and Zagnit’ko, 1981; Kulkarni et al., 2002; Jung et al., 2018):

\[
N_i = \frac{I}{e Z_{ion} E A}
\]

where \(I\), \(e\), \(Z_{ion}\), \(E\), and \(A\) respectively represent the ion current (mA), the unit electron charge \((1.6 \times 10^{-19} \text{ C})\), the electric mobility of the negative ion \((1.9 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1})\) (Kulkarni et al., 2002), the electrical field strength \((\text{Applied voltage (V)/Distance between wire and collection plate (m)})\), and the surface area of the outer electrode \((3.83 \times 10^{-2} \text{ m}^2)\). For the ion concentration calculations, only the negative ion concentration was considered because an excess of negative ions is present under the negative corona used in this ESP setup. The calculated ion concentrations were plotted against the applied voltages, as shown in Fig. 3(b). As can be seen in Fig. 3(b), the calculated ion concentration was strongly correlated with the I–V characteristics. The highest ion concentration was observed for the conductive fabric setup, with the non-conductive fabric setup showing a lower concentration.

**Fig. 3.** (a) I–V characterization results and (b) the calculated ion concentration within the ESP system without fabric, with two conductive fabrics (HAS-10(S)F1SS/PML and HPS-10(S)FIL/F1SS/BSL), and with non-conductive fabric (RR-10(S)F1SS/DSL).
concentration was obtained with one of the conductive fabrics (HAS-10(S)F1SS/PML), followed by the other conductive fabric (HPS-10(S)FIL/F1SS/BSL), and followed by no fabric. Compared to the other setups, negligible ion concentration was observed with non-conductive fabric. However, some ions might have been generated with non-conductive fabric even though it does not show a significant current increase (Fig. 3(a)). Previous studies reported the generation of reactive species (e.g., superoxide species (O$_2^-$)) by introducing dielectric or insulating materials (Sudarshan and Dougal, 1986; Durme et al., 2008; Feng et al., 2017; Jung et al., 2018). Higher ion concentration was reported with dielectric material (TiO$_2$) in the ESP system, because extra ions were generated near the material’s surface (Jung et al., 2018). These results will be further evaluated in the next section.

**ESP Enhancement and Particle Removal Efficiency**

In order to study the effect of conductive and non-conductive fabrics on particle removal, submicrometer NaCl particles were used and their number concentration ($\# \text{cm}^{-3}$) was measured at the ESP exit by SMPS (Fig. S1). The experiments were conducted with conductive fabrics (HAS-10(S)F1SS/PML and HPS-10(S)FIL/F1SS/BSL), non-conductive fabric (RR-10(S)F1SS/DSL), and no fabric. Fig. S1 displays a decrease in the number concentration of particles as the voltage increases, whether the fabric was conductive or non-conductive. As mentioned in Section 3.2, an increase in the voltage causes more ion generation (Fig. 3) and therefore, more particles can be charged by the ions. However, the particle number concentration decrease was different among the cases. As Figs. S1(a) and S1(b) show, for lower voltages there was a large decrease in the particle number concentration when the conductive fabrics were inserted, but a smaller decrease with non-conductive fabric or no fabric inserted (Figs. S1(c) and S1(d)). For example, at 1 kV, all conductive fabrics showed clear reductions in particle number concentration, but a negligible change in the particle number concentration with no fabric or non-conductive fabric inserted. It should be noted that particle generation was observed at 0 kV when the fabrics were inserted in the ESP (Fig. 4). This particle generation was likely due to detachment of loosely coated particulates, microfibers, or particles left from the manufacturing process of this fabric (Bush and Snyder, 1992; Hakansson et al., 2004; Almroth et al., 2018). Even when particles are generated by some of the fabrics upon insertion, once the ESP is activated, the increased number of particles becomes negligible due to the enhanced efficiency of the ESP setup.

Based on the particle size distribution data in Fig. S1, the particle removal efficiencies depending on different particle sizes ($\eta(d_p)$), % of the ESP with conductive fabrics, non-conductive fabric, and no fabric were calculated by:

$$\eta(d_p) = \frac{N_i(d_p) - N_f(d_p)}{N_f(d_p)} \times 100,$$

where $N_i$ and $N_f$ represent the initial and final particle number concentrations of the ESP, respectively. The results for the particle removal efficiency of the ESP for each tested fabric, with their respective compiled distributions for each tested voltage, are given in Fig. 5. As can be seen in Fig. 5, the particle removal efficiencies increased, regardless of whether the fabric was conductive, non-conductive, or no fabric, as the system’s voltage was increased due to the increase in the electric field strength and more ion generation with all cases. In addition to this general enhancement of particle removal efficiency with all cases, three distinct trends were shown 1) at 1 kV and 3 kV which were lower than the inception voltages of all cases, 2) at 5 kV and 6 kV which were near the inception voltages of the conductive fabrics (Fig. 3(a)), and 3) at 7.5 kV which was higher than the inception voltages of the conductive fabrics and no fabric (Fig. 3(a)). In the cases of 1 kV and 3 kV, the applied voltages were lower than the inception voltages of conductive fabrics, non-conductive fabric, and no fabric. Therefore, corona discharge did not occur, which resulted in the low particle removal efficiency due to the poor charging efficiency with particles (Figs. 5(a) and 5(b)). The lower charging efficiency was more pronounced with smaller particles, which is due to lower ion attachment coefficients with smaller particles (Adachi, 1985; Kulkarni et al., 2002). In addition, a bell-shaped removal efficiency of particles was obtained with these voltages. There are two opposite forces acting on particles inside the ESP (electric and drag forces), and the balance between these two forces affects the particle removal efficiency (Kulkarni et al., 2002). As mentioned above, the charging efficiency decreases with decreasing the particle size, which results in the lower particle removal efficiency. On the other hand, the drag force on particles increases as the particle size is increased, which also causes the lower particle removal efficiency. Therefore, there could be a specific particle size range at which the minimum particle removal efficiency is expected. In this study, the minimum particle removal efficiency was observed between 100 nm and 500 nm of particle size, which is similar to the previous studies (Kulkarni et al., 2002; Liao et al., 2018). All fabrics show the enhanced particle removal efficiencies compared to the case without fabric, which might be because the fabrics provided a larger surface area to capture particles.
In the cases of 5 kV and 6 kV, a pronounced effect of conductive and non-conductive fabrics on the particle removal efficiency was observed. At 5 kV, one of the conductive fabrics (HAS-10(S)F1SS/PML) showed the highest particle removal at any particle size, followed by the other conductive fabric (HPS-10(S)FIL/F1SS/BSL), followed by no fabric, and finally followed by non-conductive fabric (RR-10(S)F1SS/DSL) (Fig. 5(c)). At 6 kV, conductive fabrics and no fabric showed the complete particle removal with the particle sizes larger than 50 nm, while non-conductive fabric showed the lowest particle removal efficiency at any particle size (Fig. 5(d)). According to the I–V characteristics, HAS-10(S)F1SS/PML showed the lowest inception voltage (5.0 kV), followed by HPS-10(S)FIL/F1SS/BSL (6.1 kV), followed by no fabric (6.9 kV), and no distinct inception voltage was observed with non-conductive fabric (Fig. 3(a)). Therefore, the applied voltages of 5 kV and 6 kV were near or slightly higher than the inception voltages of conductive fabrics, and were slightly lower than the inception voltage without fabric. With these voltages, corona discharge can be initiated inside the ESP with conductive fabrics, which causes the creation of more ions with conductive fabrics compared to the others. As a result, the highest particle removal efficiency was obtained with conductive fabrics, followed
by no fabric, and followed by non-conductive fabric. Between two conductive fabrics, HAS-10(S)F1SS/PML showed the better particle removal efficiency due to the higher ion concentrations (Fig. 3(b)). On the other hand, non-conductive fabric showed the increasing trend in particle removal efficiency even though the calculated ion concentration based on I–V characteristics was negligible (Fig. 3(b)). It could be due to the creation of the reactive species such as negative ions (e.g., O$_2^-$) on the surface of the non-conductive fabric as mentioned in Section 3.2.

At 7.5 kV, different particle removal trend was observed for conductive fabrics, non-conductive fabric, and no fabric (Fig. 5(e)). All cases showed complete particle removal except smaller (< 30 nm) and larger (< 700 nm) particles. This result might be due to the generation of more ions at 7.5 kV (Fig. 3(b)). The lower particle removal efficiency at particle sizes < 30 nm could be due to still lower charging (Kulkarni et al., 2002). The lower particle removal efficiency at particle sizes > 700 nm might be because of re-entrainment of particles into gas stream. Compared to no fabric, higher particle removal efficiency was observed with conductive and non-conductive fabrics at these particle size ranges, which might be due to the higher charging and the reduction of re-entrainment of particles. As mentioned in “Introduction,” the captured particles can be re-entrained into the gas stream during the process due to several possible reasons such as gas velocity and ionic wind inside the ESP (Zukeran et al., 1999; Sung et al., 2006). Previous study reported the inhibition of re-entrainment of the captured particles with fibers on the collecting electrode, which was because the fibers suppressed a backward gas flow from the collecting electrode to the gas stream by the friction between fibers (Sung et al., 2006). Our experimental result was consistent with this previous observation.

It is also worth noting that calculated specific collecting areas (SCAs) of each case (HAS-10(S)F1SS/PML: 20.4 m$^2$ (m$^3$ min$^{-1}$)$^{-1}$, HPS-10(S)F1SS/BSL: 24.8 m$^2$ (m$^3$ min$^{-1}$)$^{-1}$, RR-10(S)F1SS/DSL: 22.6 m$^2$ (m$^3$ min$^{-1}$)$^{-1}$, and no fabric (stainless steel): 25.5 m$^2$ (m$^3$ min$^{-1}$)$^{-1}$) did not show a trend toward the particle removal efficiency. This result implies that the findings in this study can be mainly attributed to the conductive properties of nonwoven fabrics.

Based on overall results, the mechanisms of particle removal with conductive fabric, non-conductive fabric, and no fabric at near inception voltage of the conductive fabric (~ 6 kV) are summarized in Fig. 6. When the conductive fabric is used, more electrons are generated on the surface of it, and thereby more ions are existed in the ESP, which results in the enhanced particle removal (Fig. 6(a)). In the case of the non-conductive fabric, few or no electrons are created on the surface of it, and so the lowest particle removal efficiency was obtained in most cases. However, reactive species (e.g., negative ions) could be generated on the surface of non-conductive fabric, which causes the increasing particle removal trend with increasing voltage in the ESP (Fig. 6(b)). With no fabric, there is neither extra electrons nor extra reactive species on the electrode’s surface (Fig. 6(c)).

CONCLUSIONS

This study examined the effect of using nonwoven conductive fabric liners in an ESP to enhance the removal of submicrometer particles. The resistivities of three test fabrics were determined, and HAS-10(S)F1SS/PML and HPS-10(S)F1SS/BSL, due to their higher conductivity, were selected as the conductive fabrics, whereas RR-10(S)F1SS/DSL was selected as the non-conductive fabric. The measured I–V characteristics of the ESP and the calculated ion concentrations indicated lower inception voltages and higher ion concentrations when the conductive fabrics were used than when either the non-conductive or no fabric was used. Furthermore, the conductive fabrics were found to enhance the removal efficiency of the ESP at voltages below 7.5 kV, which was mainly due to these fabrics generating more reactive electrons and ions, resulting in a higher number of charged particles being deposited on the collection electrode. However, at an applied voltage of 7.5 kV, higher particle removal efficiencies were observed for all of the test cases except when the particles were < 30 nm or > 700 nm, which is attributable to a lower charging efficiency with ultrafine particles and the re-entrainment of larger particles into the gas stream. It is worth noting that the use of fabric, conductive or not, inhibited the re-entrainment of captured particles into the gas stream at this voltage. Thus, increasing an ESP’s removal efficiency by adding a fabric liner potentially reduces the cleaning issues and health risks.

![Fig. 6. A schematic diagram of particle removal in ESP system with (a) conductive fabric, (b) non-conductive fabric, and (c) no fabric.](image-url)
associated with these devices. The chemical composition of nonwoven conductive fabrics can be further explored to optimize their electroconductive abilities and enhance the removal of submicrometer particles at even lower voltages.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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