Effectiveness of an In-Duct Electrostatic Precipitator in Nanoparticle Removal with Consideration of Ozone Emissions

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Effectiveness of an In-Duct Electrostatic Precipitator in Nanoparticle Removal with Consideration of Ozone Emissions

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ABSTRACT

Human exposure to ultrafine particles (UFP, < 100 nm) has been shown to have adverse health effects such as respiratory impacts and cardiovascular mortality. UFP concentrations can be elevated in occupied buildings due to prevalence of UFP sources within buildings such as combustion, heating elements, and electric motors, as well as entry with outdoor air. In-duct electrostatic air filters (ESP) have been an efficient particulate control device for reducing UFP concentrations (10 nm to 100 nm) in buildings, although they have the potential to increase indoor ozone concentrations due to corona discharge. The objective of the present study is to demonstrate a procedure for investigating the reduction of ultrafine particles, especially particle sizes < 10 nm, and the increase in ozone concentrations due to the use of residential ESP filters in a realistic residential installation. Experiments monitored size-resolved UFP levels ranging from 3 nm to 100 nm and ozone concentrations in a manufactured test house. An in-duct air cleaner was installed and operated in the central air handling unit of the house. The experiments involved two filter operating modes: ESP on and ESP off. The results indicate that for particles sized 8.2 nm to 9.8 nm the removal efficiency for the tested ESPs was less than 10 %. Adding a media filter in series with the energized filter increased removal efficiencies to 25 %, suggesting that surface area is important to removal for particles < 10 nm. Continuous operation of the tested ESPs raised indoor ozone concentrations up to six times higher than outdoor concentrations. When using three different commercial filters containing activated-carbon downstream of the installed ESP, the overall effective ozone generation rate was reduced by 25 % for one filter and not reduced by two other filters.

INTRODUCTION

There is a trend to build tighter buildings in order to conserve energy. However, tighter buildings can lead to higher indoor concentrations of contaminants with indoor sources, such as ultrafine particles (UFP, < 100 nm) if adequate levels of mechanical ventilation are not provided. Indoor UFP sources in residential buildings included combustion (stoves, candles, and cigarettes), heating elements, electric motors and chemical reactions between some airborne contaminants (Weschler 2004). UFP have been shown to have adverse health effects such as respiratory symptoms and cardiovascular mortality (Oberdörster et al. 2007). For tighter buildings with lower ventilation rates, active control strategies are needed to reduce UFP concentrations and associated potential health risks. In-duct electrostatic precipitators (ESP) are one approach to control UFP levels within low-energy residential buildings. ESPs have the benefit of low pressure drops compared to mechanical media filters. The lower pressure drop within the HVAC system may result in energy savings. However, the actual energy impacts of these lower pressure drops in residential installations depends on fan power, duty cycles and other system efficiencies and may not always be significant (Stephens and Siegel 2012).

The particle collection efficiency of an ESP is a function of particle size and several design parameters such as airflow rate, applied voltage, collection cell area, strength and distribution of the electric field (Huang and Chen 2002). Although the theory of ESP technology has been extensively studied, few studies have investigated particle removal during the operation of in-duct ESP within a residential building. Howard-Reed et al. (2003) reported on experiments in an occupied townhouse, which showed that use of an in-duct ESP could reduce fine particle concentrations (0.3 μm to 10 μm) by 55 % to 85 % compared to central fan-off conditions. Wallace et al. (2004) reported that reduction of particles (> 10 nm) up to 50 % or more was achieved by use of ESP operation. However, there are no known studies that have examined the impact of ESP on particles < 10 nm within residences. Due to energy concerns and health risks there is a need to test the efficiency of ESP at removing particles <10 nm in the challenging field environment.

Another important issue regarding the use of ESP in buildings is potential production of ozone due to corona discharge (Boelter and Davidson 1997, ASHRAE 2012). The amount of ozone generated by ESP depends on ionization voltage and wire material. Ozone has adverse health effects such as shortness of breath, chest pain, breathing distress, and severe respiratory discomfort (ASHRAE 2009; Lippmann 1989).

The objective of this study is to demonstrate a field procedure for investigating experimentally 1) the removal of UFP below 10 nm with an in-duct ESP; 2) the ozone generation due to ESP operating within a residence; and 3) the filter pressure drop for residential ESP and activated carbon filter applications. These experiments tested only a limited number of ESPs and carbon filters, and therefore the results cannot be generalized to all such devices.

METHODS

To investigate the efficacy of ESP in removing UFP, experiments were conducted in a manufactured test house with a floor area of 140 m^2 and a volume of 340 m^3 (Nabinger and Persily, 2011). A commercially available ESP filter having a dimension of 56 cm (W) × 18 cm (D) × 41 cm (H) was installed in the central forced air return of the house. This particular ESP was selected and used to demonstrate the test procedure, not due its representativeness of such devices in general. Experiments compared particle removal in the test house with the ESP on and the ESP off. The two-stage ESP filter had a voltage of 6.2 kV on the ionizing wire when operating. Candles were used to generate particles for 20 minutes with the ESP off and the house central air distribution fan on for mixing purposes. At the end of the particle generation period, the ESP filter was installed and energized and the decay of the UFP concentration was monitored. Simultaneously, the ozone concentration increase was also monitored. After the ESP was turned off, the ozone concentration decay was recorded. Three measurements were made during each experiment: 1) air change rate, 2) UFP concentration, and 3) ozone concentration.

Air change rate measurements

Outdoor air change rates were measured using periodic injection (every 4 h) of a tracer gas (sulfur hexafluoride, SF_6) and monitoring SF_6 decay using a gas chromatography and electron capture detector (GC-ECD) in seven rooms of the test house with closed windows. A central air distribution fan, which is a part of the heating and cooling system in the building, was always on to mix the interior air at the rate of 2,300 m^3/h to 3,000 m^3/h or about 8 air changes per hour. Air change rates were calculated for each of the seven rooms by regressing the logarithm of the SF_6 concentration against time over a 70-minute period (ASTM 2011). The average outdoor air change for the test house during the experiments was 0.31 h^{-1} with a 37 % RSD.

Measurement of size-resolved UFP

A Scanning Mobility Particle Sizer (SMPS) Spectrometer that consists of a nano-differential mobility analyzer and water-based condensation particle counter was used to monitor size-resolved UFP ranging from 3 nm to 100 nm. The SMPS scanned 97 particle size ranges during each 2.5 minute scan. The SMPS was located in the master bedroom of the test house, while the indoor particle source was located in the kitchen (Figure 1).

Background UFP concentrations were collected for 20 minutes prior to the ignition of the indoor source. UFP concentration data for each sampling period was summed for every five contiguous particle bin sizes. The particle removal efficacy of the ESP was determined using a whole house mass balance on each summed bin size using the method outlined by Stephens and Siegel (2012). Particle concentrations were analyzed only when the total UFP concentration was below 20,000 cm^{-3} to reduce the impact of particle coagulation and growth on the decay rates (Rim et. al. 2012). Outdoor UFP concentrations were not directly measured during this analysis. Previous work has characterized the particle penetration for UFP in this test house (Rim et al. 2012). Outdoor particle concentrations were calculated as the multiple of the average background indoor concentration and the previously observed particle entry rates for the particles of interest (3 nm to 15 nm) in the test house. Particle penetration factors were assumed to be 0.2 based on the previous studies in the test house cited above.

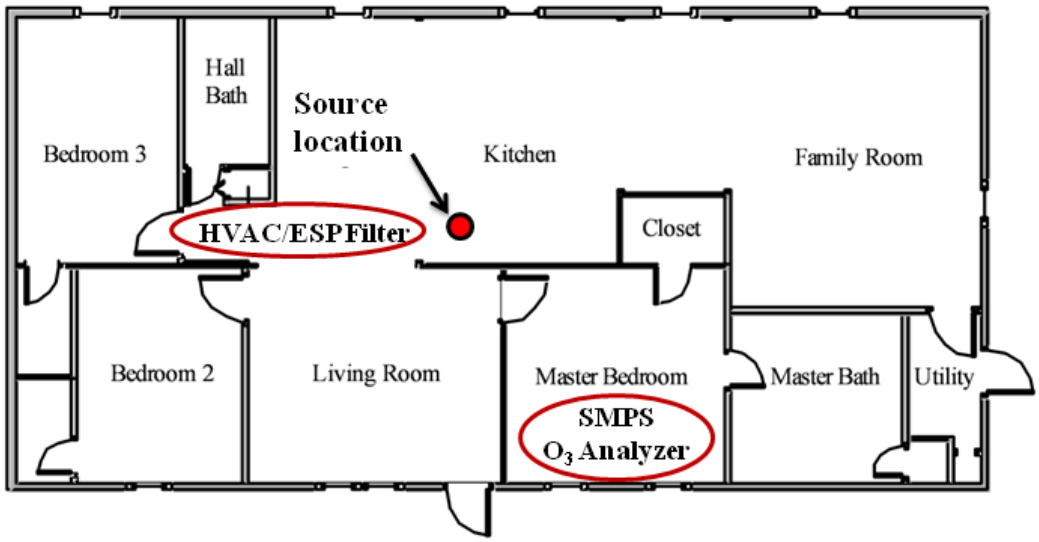

Figure 1. Test house layout with locations of the particle source, ESP and monitoring equipment

Ozone concentration monitoring

Ozone concentrations were measured at the center of the master bedroom using an absorption ozone analyzer. One minute average ozone concentrations were logged throughout the duration of each experiment. Prior to each test with when the ESP was running, the ozone indoor and outdoor ozone concentrations were measured for at least five minutes. On average the initial indoor ozone concentration was 2.1 ppb_v (64 % RSD), while the outdoor ozone concentration averaged 14 ppb_v (41 % RSD).

A mass balance model was applied to determine the ESP generation rate of ozone. The model (Eq (1)) assumes the outdoor ozone level was constant at the concentration measured at the beginning of the experiment and the outdoor air change rate was the value measured by tracer gas decay.

$$\frac{dC}{dt} = p\lambda C_o - \lambda C + \frac{E}{V} - \frac{K_H}{V}C \qquad \text{Eq (1)}$$

Where:

t = Time (h)
C = Indoor ozone concentration (ppb_v)
C_o = Outdoor ozone concentration (ppb_v)
p = Ozone penetration factor (-)
λ = Air change rate (1/h)

E = Effective ESP ozone emission rate (m^3 ppb_v/h)

V = Test house volume (m^3)

K_H = Average whole house ozone deposition rate (m^3/h)

The model was solved for a time dependent solution as shown in Eq (2).

$$C = C_{t=0}e^{-\left(\lambda+\frac{K_H}{V}\right)t} + \frac{\left[\lambda p C_o + \frac{E}{V}\right]}{\lambda + \frac{K_H}{V}}\left(1 - e^{-\left(\lambda+\frac{K_H}{V}\right)t}\right) \quad \text{Eq (2)}$$

Using the decay data after the ESP was turned off (E=0, $C_{t=0}$ = maximum ozone concentration), the average whole house ozone deposition rate (K_H) and ozone penetration factor (p) were determined from the time-dependent ozone concentration data using a least sum of squares regression model fit of the measured data. The effective ESP ozone emission rate (E) was determined using a second least sum of squares regression fit of the ozone concentration data measured when the ESP was on, and the whole house ozone deposition (K_H) and penetration factor (p) values calculated from the ozone decay data.

Test conditions

One hypothesis for particles smaller than 10 nm is that Brownian motion is the primary removal mechanism and that particle charging in the ESP is limited. In that case, the removal of particles smaller than 10 nm will be dependent primarily upon filter surface area and not the charge imparted by the ESP. To investigate this hypothesis four types of experiments were performed to determine the efficacy of ESP at removing UFP < 10 nm (Table 1). The effect of surface area was seen in comparing the first three types of experiments. Removal rates from each experiment type were averaged for each bin size. Since the tested ESP was found to generate ozone, the ability of three commercially available activated carbon filters to remove the generated ozone was investigated. These particular carbon filters were selected based on their availability and to demonstrate the test procedure, not based on their representativeness of carbon filter devices in general.

Table 1. Experiment conditions

Experiment Type	ESP	Carbon Filter	Number of Experiments
1	None	None	6
2	In Duct, Not On	In Duct	4
3	On	In Duct	13
4	On	None	3

RESULTS AND DISCUSSION

Table 2 presents the pressure, airflow rate and power consumption for the different operating conditions. ESP manufacturers advertise energy savings of using ESP filters over traditional media filters due to lower pressure drop. The pressure drop was 21 % lower for the tested ESP compared to the carbon media filter with the ESP (the media filter did not have a MERV rating). The ESP only experiment had 15 % greater airflow and drew 11 % more fan power than with ESP operating with the media filter. Since the fan was on for the entire experiment, adding the media filter reduced the energy consumed between experiments 3 and 4. In actual operation, the higher airflow for the ESP may lead to shorter duty cycles and energy savings compared to a media filter (assuming compressor loadings and duct leakage are the same). However, Stephens et al. (2010) found energy impacts of filters with different MERV ratings (2 versus 11, a pressure drop difference of 45 Pa) were within the measurement errors of the instruments and energy differences small compared to the other factors such as system operation, installation and maintenance. Therefore, additional work is needed to fully understand the potential energy impacts associated with lower ESP pressure drops.

Table 2. Pressure drop and airflow rate associated with ESP and carbon filter. Values in parentheses are standard deviations of measured values.

Experiment	Pressure drop (Pa)	Airflow rate (m^3/s)	Fan Power (W)	ESP Power (W)
1. No ESP	9.1 (±1.2)	0.82 (±0.06)	617	0
2. ESP in place, not on[1]	23.5 (±0.7)	0.76 (±0.12)	605	4
3. ESP only	23.5 (±0.7)	0.76 (±0.12)	605	42
4. ESP with carbon filter	109.5 (±4.6)	0.64 (±0.08)	540	42

[1]The ESP drew standby power with the switch in the off position. Pressure drop, airflow rate and fan power were the same value as Experiment 4.

Some studies have shown ESPs generate ozone at significant levels (Boelter and Davidson 1997, ASHRAE 2012), while other studies have measured low ozone concentration or no ozone generation (Bowser and Fugler et. al. 2002, Wargocki et. al. 2008). The generation of ozone from ESPs can be problematic in and of itself, as well as due to secondary ozone reactions can occur in the residence producing gases and particles that affect human health (Weschler 2004). Figure 2 shows examples of ozone concentration profiles observed with the ESP filter operating and the various carbon filters installed. The ozone concentration increased by a maximum of 70 ppb_v after continuous operation of ESP filter in the test house for about 18 h (Figure 2a). For a frame of reference, the U. S. EPA National Ambient Air Quality Standard 8-hour standard for outdoor air is currently 75 ppb_v (U.S. EPA 2005). Ozone can be removed by reaction with activated carbon (Kunkel et. al. 2010). Three different commercial brands of media filters containing activated carbon were tested for their ability to remove ESP generated ozone. The filters varied in their construction as well as the mass of embedded activated carbon (Table 3). Figure 2b shows that a commercially available filter containing activated carbon removed on average 39 % of the ozone. While not shown in the figure, the filter performance degraded to about 26 % removal after 100 hours of operation. Among the three activated carbon filters tested, the filter shown in Figure 2b (Filter 1) was the only one that removed a substantial amount of ozone. The average whole house deposition value of ozone in the test house, due to losses associated with ductwork and surfaces in the house, was 376 m^3/h (RSD 23 %).

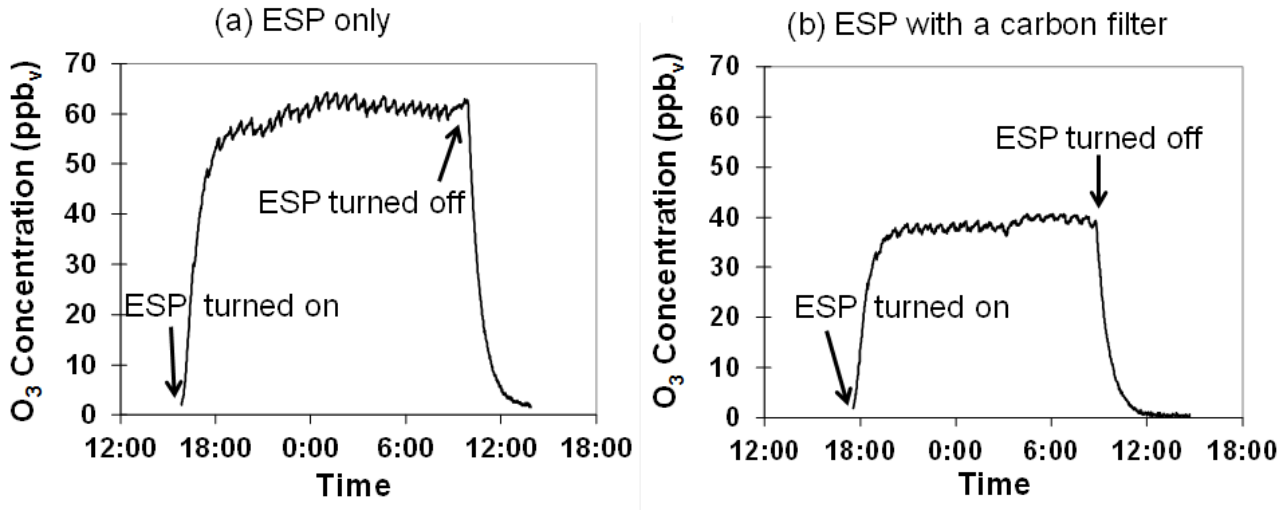

Figure 2 Ozone concentration profile examples: (a) ESP only and (b) ESP with a carbon filter downstream – this carbon filter was one of three commercially purchased activated carbon filters, which was the most efficient filter in removing ozone among the filters tested.

Table 3. Activated carbon filter performance. (Standard deviations of replicate measurements are shown in parenthesis.)

Filter	Manufacture Rating	Activated Carbon Mass (g)	Average Steady-State Ozone Concentration (ppb_v)	Average Effective Ozone Generation Rate (mg/h)
None	-	-	57.6 (±5.5)	51.3 (±6.0)
1	MERV 11	118	35.2 (±2.2)	38.7 (±6.3)
2	MERV 13	Unknown[1]	54.3 (±1.6)	51.2 (±7.1)
3	FPR 5	Unknown[1]	53.6 (±1.8)	56.1 (±7.7)

[1] Visual inspection was the activated carbon mass in filter 1 was greater than 2 and 3.

This study is limited to only one residential ESP unit and three activated carbon filters, which are not necessarily representative of all available technology. Furthermore, the test procedure used in this study created a worst-case scenario for ozone emissions due to the continuous operation of the ESP and central fan. The ozone emission in actual building environments may be less since the central mechanical fans often run intermittently rather than continuously, depending on the building heating or cooling load and the heating and cooling capacity of the equipment.

This study was focused on the demonstration of test procedures for quantifying the removal of particles < 10 nm in a test house environment since the effectiveness of ESPs in removing particles greater than 10 nm has been demonstrated elsewhere (Wallace et al. 2004; Howard-Reed et al. 2003; Morawska et al. 2002). Figures 3a, 3b, and 3c show size-resolved UFP concentration data collected with varied operating conditions of ESP and carbon filters in the air handling unit while burning a candle in the kitchen. These figures present a 20-min particle emission and subsequent decay period. The figures indicate that the majority of particles from candle burning are < 10 nm. The slope of the concentration decay for 30 minutes after the candle burning increased (faster removal) when the ESP and carbon filter operated compared to both filters not operating.

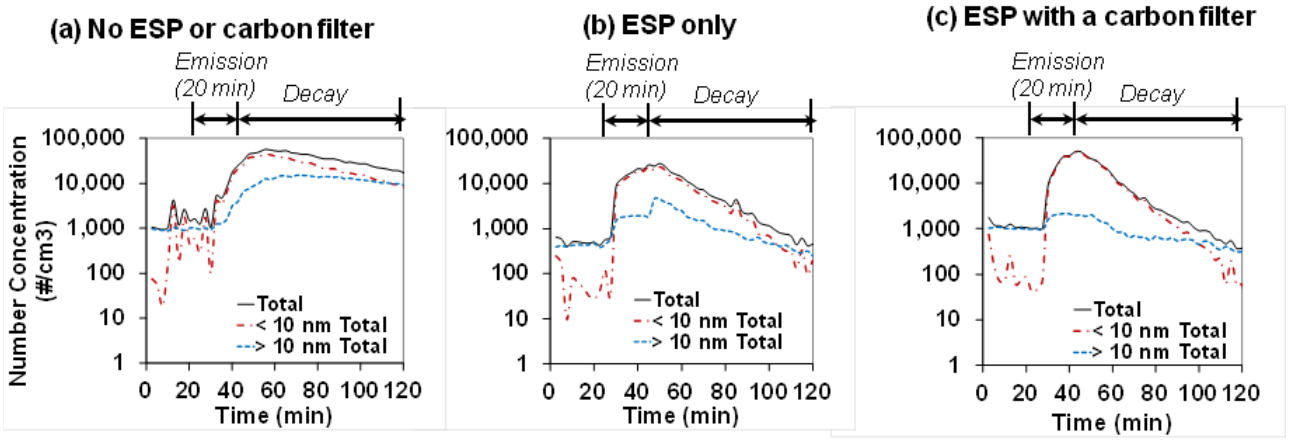

Figure 3 Particle concentrations (a) neither ESP nor carbon filter operating (central fan off); with ESP only operating; (b) with ESP and an activate carbon media filter operating.

Figure 4 illustrates size-resolved particle decay rates for particles < 10 nm for four cases: 1) ESP energized and the media filter in place (blue diamond), 2) ESP and media filter in the duct, but with the ESP not energized (red square), 3)

ESP in place and energized with no media filter (green triangle), and 4) ESP not energized or no activated carbon filter in place (black circle). The decay rates for no filters (4) and the energized ESP without a media filter (3) are similar for particles less than 10 nm. The overall removal efficiency for the energized ESP alone for particles in the 8.2 nm and 9.8 nm bins sizes was less than 10 % (removal rates below 8.2 nm could not be calculated due to incomplete deposition data in these particle sizes). This result indicates for particles < 10 nm there is only a marginal increase in particle removal with only the ESP operating. It may be that charging efficiency for particles < 10 nm is relatively low compared to larger particles. In other words, the voltage on the ionizing wire of the ESP, i.e., 6.2kV, may not be large enough to charge small particles (<10 nm) to the extent necessary to travel the distance required to reach the collecting plates in the time frame the air passes through the ESP (Huang and Chen 2002).

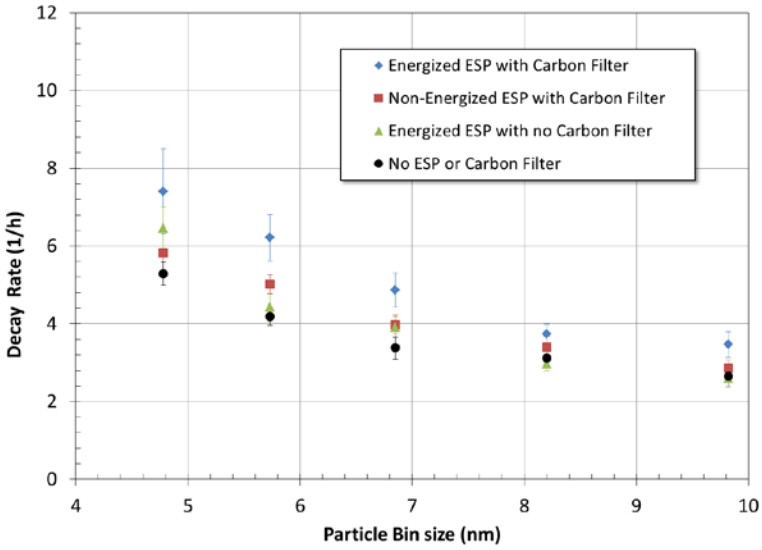

Figure 4: Comparison of particle decay rates for particle sizes less than 10 nm for experiments with ESP on and off. Central furnace fan was running continuously for all three cases. Error bars show the standard deviations of the averages.

If Brownian motion is an important removal mechanism for removal of particles less than 10 nm, adding more surface should increase the decay rates. When the media filter was added to a non-energized ESP, the particle decay rate increased slightly compared to the no filter and energized ESP only experiments (Figure 4). This result implies that surface area, and hence Brownian motion, plays a role in the removal of particles of this size. When the energized ESP and media filters are both installed they remove particles below 10 nm at a greater rate (sometimes more than 1/h) than all other conditions. These results indicate that for this ESP the collection plates alone may be too far apart for particles < 10 nm to travel for effective removal. The addition of the media filter provides extra surface area so the charged particles have a shorter distance to travel, increasing removal. Hence, for particles less than 10 nm, both particle charging and Brownian motion are likely important removal mechanisms. However, even at the increased removal rates of the combined energized ESP and media filters, the overall removal efficiency for particles in the 8.2 nm and 9.8 nm bins sizes was less than 25 %.

CONCLUSION

This study investigated the efficacy of a commercially available ESP in removing ultrafine particles in a manufactured test house as a demonstration of a test procedure for application to field-installed units. Although previous studies show that ESPs can be effective in removing particles greater than 10 nm in a cost-effective way, this study showed that the tested ESP did not significantly enhance the removal of particles smaller than 10 nm. Whether this result applies to other ESPs will require additional experiments. Ozone generation from an ESP is another issue associated with these devices. The three commercially available activated carbon media filters tested in this study did not effectively remove ozone from the tested ESP under real world operating conditions. These results, particularly if they are shown to apply more generally, imply the need to evaluate carefully the impacts on energy cost, particle removal, and ozone generation associated with ESPs and other air cleaning devices.

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