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Design and Development of an Electrostatic Screen Battery for Emission Control (ESBEC)

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Abstract

Current diesel particulate filters (DPFs) can effectively capture the exhaust particles, but they add to engine backpressure and accumulate particles during their operation, which results in the need to regenerate the DPFs by burning off the collected particles periodically. This regeneration results in aerosol emissions, especially in the 10–30 nanometer size range and contributes to ultrafine particle pollution. In this research, we designed and developed a prototype of a novel diesel exhaust control device: the Electrostatic Screen Battery for Emissions Control (ESBEC). The device features high particle collection efficiency without adding to the exhaust backpressure and without the need for thermal regeneration of the collected particles. The ESBEC consists of a series of metal mesh screens coated with a superhydrophobic substance and an integrated carbon fiber ionizer to charge the incoming particles. Multiple pairs of screens (e.g., 5 pairs) are arranged in a battery, in which one screen of each pair is supplied with high voltage, and the other is grounded, producing electrostatic field produced across the screens. The application of a superhydrophobic coating onto the screens allows easy removal of the collected particles using liquid without the need for thermal regeneration. The current prototypes of the device were tested with fluorescent polystyrene latex (PSL) particles of 0.2 and 1.2 μm in size and at 25 and 105 L/min sampling flow rates. The average collection efficiency was ~87% for 0.2 μm and ~95% for 1.2 μm PSL particles. In addition, the ESBEC was tested with actual diesel exhaust particles; here its performance was verified by visually inspecting deposition of particles on an after-filter with the device ON and OFF. In the next stages of this work, the ESBEC will be challenged with diesel exhaust at different mass concentrations and for different collection time periods.

Keywords

Diesel Particulate Filter; diesel emissions; Electrostatic collection; Wire Screen; superhydrophobic surface

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INTRODUCTION

Over the past six decades, the number of internal combustion vehicles has dramatically increased worldwide (El-Hinnawi & Hashmi, 2013; Nygren & Andersson, 2000). While the vehicles have enormously benefited people's lives, they also brought a number of environmental concerns, such as air pollution and contribution of emissions to climate change (Creamer & Gao, 2015; Jean-Baptiste & Ducroux, 2003). Primary air pollutants such as carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides, particulate matter, directly emitted by vehicles (Parrish, 2006; Reito et al., 2015), as well secondary pollutants, such as ozone and fine particulate matter, formed as a result of primary emissions and ensuing chemical reactions and environmental processes can have serious effects on health and the environment (Katsouyanni, 2003; Schlesinger & Cassee, 2003). Among internal combustion engines, compression ignition (diesel) engines are widely used in heavy-duty trucks, stationary engines (e.g., agriculture engines, water pumps, etc.), and power generators. Because of the differences in thermodynamic processes between spark-ignition and compression-ignition engines, diesel combustion engines typically have better efficiency compared to gasoline internal combustion engines and offer better mileage in automotive applications (Sullivan et al., 2004). However, diesel combustion engines emit substantial amounts of nitrogen oxides (NO_x) and particulate matter (PM), both of which are criteria pollutants (Johnson, 2009; Wang et al., 2015). The emitted PM consists of an uncombusted carbon core, adsorbed hydrocarbons from engine oil and fuel, adsorbed sulfates, water, and inorganic materials such as those produced by internal engine abrasion (Ålander et al., 2004; Kerminen et al., 1997). Diesel vehicles are responsible for 72% of PM emissions from mobile sources (Lawal & Araujo, 2012). Regulatory agencies have been promoting introduction of tighter diesel PM emission standards for passenger cars, heavy-duty vehicles, marine vessels, and even stationary sources to ameliorate health and environmental concerns related to particle emissions from diesel engines (Abdul-Khalek et al., 1999; Holman et al., 2015; Kotchenruther, 2015; Lurmann et al., 2014; USEPA, 2014). In order to meet the emission standards, a number of diesel particulate filters (DPF) have been developed and implemented to minimize diesel soot emissions (Khair, 2003; Konstandopoulos et al., 2000b; Reito et al., 2015). A conventional DPF is designed to remove particulate matter from the exhaust gas due to Brownian diffusion and direct interception of the particles moving through the filter (Konstandopoulos et al., 2000a). DPFs are usually made of ceramic (e.g., cordierite or silicon carbide) or metallic (e.g., sintered metal, metal foam) core encased in a steel shell. Several different configurations, such as wall-flow and honeycomb structures, are available. (Howitt & Montierth, 1981). DPFs, as part diesel exhaust reduction technologies, are added in brand-new vehicles and are also sold as after-market devices for existing vehicles (Mayer Andreas, 2008). DPFs capture solid and liquid matter within the exhaust gas and can be an effective means of reducing both the particulate mass and particulate number emissions (Joulin et al., 2003; Kittelson David B., 1998; Mayer A. & Buck, 1992). However, the current DPFs are not very effective at capturing ultrafine particles (i.e., less than 100 nanometers in diameter) (Joulin et al., 2003), which have been linked to increased morbidity and mortality (Nemmar et al., 2003; Wichmann, 2007). In addition, since the captured particles continue to accumulate inside the DPF during the engine's operation, this accumulation of PM causes pressure in the exhaust

system (called backpressure) to increase (Bahr, 2013). As the backpressure increases, more work has to be done by the engine to push the exhaust gasses out. Thus, the fuel consumption increases to provide the extra power necessary to overcome the increased backpressure, and engine performance is affected by variable backpressure conditions (Hield, 2011). Thus, a regenerative or cleansing process of the DPF is required (Fino et al., 2003; Koltsakis & Stamatelos, 1997). In all traditional DPFs, the regeneration is achieved by burning off the collected material which requires consumption of fuel and creates secondary aerosol emissions, especially in the 10 to 30 nm size range (Bikas & Zervas, 2007). Particles produced during the DPF regeneration are not captured and are emitted into the air thus contributing to air pollution.

The recent development of the traditional DPFs has been mostly focused on improving their material and structure (Kamp et al., 2015). At the same time, to reduce the outstanding DPF issues, such as backpressure and the need to burn off the collected particles, there have been attempts to apply electrostatic precipitation (White, 1965) to collect diesel exhaust either as a stand-alone method (Saiyasitpanich et al., 2007) or in combination with traditional DPFs (H. Hayashi, 2009; Sato et al., 2005; Xiancheng et al., 2001). These investigators demonstrated successful removal of particles from the air, but the described technologies still relied on thermal oxidation (burn-off) to regenerate the collection media thus leading to emissions of nano-sized particles and carbon dioxide, as a byproduct of burn-off.

In this paper, we propose a novel design and approach to applying electrostatic precipitation for the removal of particulate matter from diesel emissions. In the described device, diesel exhaust particles are electrically charged and then removed using multiple wire screens (i.e., a screen battery) incorporated in an open channel holder. The utilization of wire screens results in a negligible pressure drop (low backpressure). Moreover, the screens are covered with a superhydrophobic substance (i.e., water repellent material), and, as a result, the collected particles can be easily removed by washing them off without the need for thermal regeneration. Thus, no additional particles and carbon dioxide are produced and emitted. The liquid used for washing could be captured and the washed-off carbon recovered for various industrial applications (e.g., tire, rubber, paints, etc.).

The goal of this study is to introduce the concept of this diesel emissions collector and investigate how the various design and operation parameters (e.g., the number of screen sets, the air gap between the screens, mesh size of the screens and applied voltage) affect its performance. The majority of the tests, including the removal of the collected particles from the screens, were carried out with fluorescent polystyrene latex (PSL) particles. The capture of diesel exhaust was investigated on a pilot scale and will be fully addressed in separate studies.

MATERIALS AND METHODS

Design of the Electrostatic Screen Battery for Emission Control (ESBEC)

The design of the initial ESBEC prototype (1st generation) is shown in Fig.1. Fig. 1a demonstrates the concept of the proposed ESBEC structure as a two-stage electrostatic precipitator with separate charging and collection sections. To charge the incoming particles

in the initial prototype, we used a modified, commercially available car ionizer (AS 150, Wein Products section, Inc., Los Angeles, CA): its cover screen was removed, and the exposed needle faced a ground electrode located at the bottom of a non-conductive pipe. The charged particles then enter a collection section consisting of multiple sets of mesh screens pairs positioned in series. One screen in each pair is supplied with high voltage, and the other is grounded, producing electrostatic field across the screens within the pair. Fig. 1b is a picture of the collector of the 1st generation ESBEC. Here, the collector consists of a series of 24×24 mesh size (i.e., the number of openings per linear inch) copper screens with a wire diameter of 0.028 inches and screen porosity (i.e., the fraction of open area) of 44%. The screens are coated with a superhydrophobic material (HIREC-1450, NTT Corporation Inc., Japan) to facilitate removal of the collected particles.

Once the ESBEC (i.e., the 1st generation ESBEC) concept was proven to be technically feasible, its design parameters were optimized for easier handling (i.e., less complex and easier to assemble) rather than its performance, as described below. Based on the insights gained through the optimization process, we designed the 2nd generation ESBEC, where a new charger was incorporated with the collector, and they operated as a single unit (Fig. 2a). The 2nd generation ESBEC was designed as a single, heat-resistant unit that could eventually be tested with actual diesel exhaust.

Fig. 2b shows pictures of the 2nd generation ESBEC prototype, including collector housing, inner screen holders, a closed unit with screens inside, and a charger. The collector consists of two half-cylinder shells holding the screens. The first screen (far left screen in Fig. 2a) acts as a ground electrode for the charger. Once the “shell” is closed, it forms a cylinder of 1.5 inches in diameter and is inserted into a housing tube forming an air-tight unit. A carbon fiber brush (i.e., ion source) is affixed in the housing perpendicular to the air flow and facing the ground screen. The carbon brush contains ~600–800 carbon fibers with the diameter of approximately $7 \mu\text{m}$ (VC-36S, Formosa Plastics Co., Taiwan). The inner screen holders and the outer shell were fabricated by 3D printing through www.shapeways.com. When operated, the high voltage between the first grounded screen and the tips of the carbon brush creates a strong electrical field producing emission of ions from the brush, and the ions attach to the incoming airborne particles. As the charged particles move further into the battery, the screens connected to a voltage with polarity opposite to the sign of particle charge attract the particles and remove them from the air stream. In order to improve the performance of the 2nd generation ESBEC, screen sets had different porosity and wire diameter as described in Table 1.

Experimental setup to test ESBEC—Fig. 3 shows the schematic diagram of an experimental setup used to investigate the performance of the ESBEC. The setup was housed inside a Class II Biosafety cabinet (NUAIRE Inc., Plymouth, MN).

The HEPA-filtered airflow through the system was provided by a vacuum pump located downstream of the system and operated at either $q_s = 25$ or 105 L/min , depending on an experiment. A six-jet Collision nebulizer (Mesa Labs, Inc., Butler, NJ) was used to generate green fluorescent PSL particles (Duke Scientific, Palo Alto, CA) from a liquid suspension at a flow rate $Q_A = 5 \text{ L/min}$ (pressure of 68.9 kPa). The test aerosol was diluted and dried with

the air flow rate $Q_D = 20$ L/min (or 100 L/min). The aerosol stream passed through a charge neutralizer (Po-210, Amstat Industries Inc., Glenview, IL) built-in in a 0.035 m duct; the electrically neutralized particles (at Boltzmann charge equilibrium) were then negatively charged by an ionizer (AS 150, Wein Products Inc., Los Angeles, CA). This separately positioned ionizer was only used when testing the 1st generation ESBEC. When testing the 2nd generation ESBEC, a built-in carbon fiber ionizer was used as described above. A stable DC power supply (BK Precision, Yorba Linda, CA) provided power to the ionizer; its charging intensity was controlled by adjusting the voltage and current settings (e.g., 12V/50mA). The negatively charged aerosol particles entered ESBEC at a flow rate Q_S and were collected on the screens by the action of the electrostatic field. Collection voltage applied to the 1st generation ESBEC varied from +7 to +9 kV (Bertan Associates, Inc., Valhalla, NY). When testing the 2nd generation ESBEC, carbon fiber ionizer was operated at voltages from -9 to -10 kV, while the collector was operated at voltages from +9 to +12 kV (Bertan Associates, Inc., Valhalla, NY). Air flow rates through the system were monitored by mass flowmeters (TSI Inc., Shoreview, MN). Particles not removed by the ESBEC were collected by a 47 mm glass fiber after-filter (Type A/E, Pall Inc., East Hills, NY) positioned downstream of the ESBEC.

Particles of 0.2 and 1.2 μm in geometric diameter were used in our tests as they represent the typical sizes of diesel exhaust particles, where particles typically are less than 2.5 μm in diameter with a substantial fraction (based on mass distribution) of particles being around 100–200 nm in diameter (Abdul-Khalek et al., 1999; Kittelson D. B., 2001; Zhu et al., 2002).

Testing of the 1st generation ESBEC

Experimental procedure: 1) The overall collection efficiency of ESBEC, η , was determined by comparing particle number concentration upstream ($C_{upstream}$) and downstream ($C_{downstream}$) of the device using an optical particle counter (model 1.108, Grimm Technologies Inc., Douglasville, GA) through probes positioned upstream and downstream of the collector (shown in Fig. 3). The Grimm OPC measures particles between 0.3 μm and 20 μm , and its detection limit is 1 to 2×10^6 counts/liter. The sampling flow rate of the Grimm OPC is 1.2 L/min. The overall collection efficiency is defined as:

$$\eta = 1 - \frac{C_{downstream}}{C_{upstream}} \quad (1)$$

ESBEC was operated at 25 L/min (air velocity of 0.37 m/s through the device). Use of direct reading instruments allowed for quick testing of different ESBEC configurations.

2) Particle deposition inside ESBEC, including particle deposition on each individual screen, was examined using a fluorometric method (Han & Mainelis, 2008; McFarland et al., 2010). The airborne number concentration of used 1.2 μm PSL particles was about $2.5\text{--}3.0 \times 10^5$ /Liter which translates to an airborne particle mass concentration of approximately 238–285 $\mu\text{g}/\text{m}^3$. After each test, each collection screen was soaked in 5 mL of ethyl acetate in a glass container for 1 hour to elute the fluorescein dye from the collected PSL particles, while the

after-filter was soaked in 5 mL of ethyl acetate for 4 hours to ensure that PSL particles on the filter are dissolved (Han & Mainelis, 2008). The relative mass of PSL particles on each collection screen was quantified by analyzing fluorescence of each extract using a digital filter fluorometer (Turner Quantech model FM109515, Barnstead/Thermolyne Inc., Dubuque, IA) (Han and Mainelis, 2008). The collection efficiency of each screen, η_i , and the overall collection efficiency η , were determined as follows:

$$\eta_i = \frac{C_i}{C_{TOTAL}} = \frac{C_i}{\sum_i C_i + C_{after-filter}} \quad (2)$$

where C_i = aerosol mass concentration on each screen based on fluorometric reading, and $C_{after-filter}$ is particle mass concentration on the after-filter. The C_{TOTAL} is the sum of aerosol particle mass deposited on all individual screens and on the after-filter.

3) Once the design parameters of the 1st gen. ESBEC were finalized, it was pilot-tested with particles from actual diesel exhaust. Here we used a diesel-powered electrical generator (Model YDG 5500 EE, Yanmar Corp., Adairsville, GA) as a source of diesel emissions at the Controlled Environment Facility (CEF) of Rutgers Environmental and Occupational Health Sciences Institute. This facility, including diesel generation, is described elsewhere (Sunil et al., 2009). In our tests, the diesel exhaust mass concentration was 300 $\mu\text{g}/\text{m}^3$, and ESBEC was tested at 25 L/min sampling flow rate for 60 min sampling time. Its performance was determined by visually inspecting and contrasting the after-filter appearance with ESBEC power ON and OFF. It is important to mention that due to a particular setup of the test facility, once the diesel exhaust reaches the CEF it already is at room temperature. This allowed us to test the 1st gen. prototype which was not built with heat-resistant materials.

Investigated design parameters of the 1st generation ESBEC: In these tests, the ESBEC was operated at a sampling flow rate of $Q_S = 25$ L/min, 12 V/50 mA ionizer's voltage/current and a +7 kV collection voltage, unless indicated otherwise. Iterative design and testing steps were applied to optimize the following (1) the number of screen pairs, (2) the gap between the ground and collection screens in each pair, (3) input current of the commercial ionizer, and (4) the mesh size of the screens:

1. ESBEC was tested with 1, 2, 3 and 5 pairs of screens made of copper (McMaster-Carr Co., Elmhurst, IL). This material was chosen because of its good electrical conductivity. The screens were of plain weave type (i.e., woven-wire screen) with the wire diameter of 0.028 inches and 24 $\times$ 24 mesh size. The gap between each ground and collection screen was set at 19.05 mm (0.75 inches).
2. Next, using 3 pairs of screens of 24 $\times$ 24 mesh size from the above step, we compared the performance of the ESBEC at two different gaps between the ground and collection screens: 0.75 and 1.5 inches.

3. Using 3 pairs of screens with a 1.5-inch gap between the screens, performance of the ESBEC was compared at two ionizer currents adjusted by a DC power supply (BK Precision, Yorba Linda, CA): 24 mA versus 50 mA. An input DC voltage of 12 V was applied as per the ionizer manufacturer's recommendation, and it resulted in the ionizer's output voltage of approximately -10 kV as determined by a high voltage probe (HVP-40DM, Pintech Electronic LTD., China).
4. The tests were carried out with two different configurations of woven wire mesh screens: wires of 0.028 inches in diameter, 44 % porosity, and 24×24 mesh size versus wires of 0.009 inches in diameter, 30 % porosity, and 100×100 mesh size. In this experiment, we tested 3 and 5 pairs of screens. When 3 pairs of screens were tested, there was a 1.5-inch gap between the screens and the ionizer was operated at 12 V/24 mA. For 5 pairs of screens, there was a 0.75-inch gap between the screens and the ionizer was operated at 12 V/50 mA setting.

Removal of the collected particles: In order to determine the efficiency of removal of the collected particles, one pair of screens (ground and collecting screens) was coated with a superhydrophobic spray and left to dry at 60°C for 1 hour (Han & Mainelis, 2008). Removal of the 1.2 μm fluorescent PSL particles captured on the screens at a 25 L/min sampling flow rate was compared with and without a superhydrophobic coating of the screens. After 10 min of sampling, each screen was submerged in 5 mL water in a glass container, which was then swirled for ~5 s. The suspension was then transferred into a 50 mL sterilized tube, and fluorescence intensity of a 0.1 mL aliquot was measured. This 0.1 mL hydrosol with fluorescent PSL particles was kept in an incubator at 60°C for about 1 hour to evaporate the water, and then 5 mL of ethyl acetate was added to dissolve the PSL particles within 10 min (Han & Mainelis, 2008, 2012). The mass of PSL particles remaining on the screens (not removed by 5 mL water) was also quantified by eluting them using 5 mL ethyl acetate in a glass container for 10 min. This allowed for comparison of removal efficiency.

Testing of the 2nd generation ESBEC: Once the design parameters of the 1st generation ESBEC were finalized, the 2nd generation ESBEC was built as described above. Its efficiency was determined using the experimental setup in Fig. 2 and fluorometric method to analyze the overall collection efficiency and particle deposition on individual screens. Differently from the 1st ESBEC generation, two high voltage power supplies were used: one for the charger and the other for the collector. The collection efficiency was investigated at a sampling flow rate of $Q_S = 105$ L/min. This flow rate was selected so that the resulting air velocity of 1.5 m/s through the ESBEC would be within the range of air velocities in actual conventional diesel particulate filters. The latter is estimated based on a typical range of DPF flow rates (11–680 m³/hour) and diameters (0.12–0.27 m) (Dou, 2012; Zhong et al., 2012).

RESULTS AND DISCUSSION

Fig. 4 presents a performance of the 1st generation ESBEC prototype when collecting 1.2 μm PSL as a function of various parameters. First, we investigated how the ESBEC collection efficiency changes depending on the number of screen pairs used (Fig. 4a). As could be expected, the collection efficiency increased with the increasing number of screen

The ESBEC configuration resulting from experiments described above (5 sets of 24×24 mesh size screens, 19.05 mm gap between screens, ionizer operated at 12 V/50 mA and collection voltage of +7 kV) was challenged with diesel exhaust at a concentration of $300 \mu\text{g}/\text{m}^3$. The collector's performance was determined visually (presented in Supplemental materials (Fig. S1)) based on the appearance of the after-filter with ESBEC ON and OFF (15 min operation in each case). As could be clearly seen, when the ESBEC was operational (charging and collection voltages were on) the filter was much cleaner than when the ESBEC voltages were turned off and diesel exhaust particles passed through it.

The experiments performed above showed the feasibility of ESBEC to capture particles from diesel exhaust. Over time, the screens would fill up with diesel particles and the particles would have to be removed to ensure operation of ESBEC. To avoid the use of thermal regeneration (burn-off), which creates additional particles, we propose to coat the screens with a superhydrophobic material to facilitate an efficient wash-off of the collected particles. Thus, the efficiency of particle removal from the screens was investigated as described in Methods. The average particle removal efficiency from screens without superhydrophobic coating was $54 \pm 0.3\%$, while the removal efficiency from screens with superhydrophobic coating was $78 \pm 2\%$. Thus, the coating of screens facilitates the removal of collected particles. Use of different superhydrophobic substances might improve the removal efficiency even further.

We also investigated how the collection efficiency changes once the collection screens are washed multiple times. Here, one pair of screens coated with superhydrophobic material was used to collect $1.2 \mu\text{m}$ PSL for 10 minutes at 25 L/min sampling flow rate. The collected particles were washed off and the procedure — collection and washing — was repeated 4 more times (5 repeats total). The average collection efficiency of one screen pair was $45 \pm 3\%$. The *COV* of the collection efficiency over 5 cycles was less than 6.0 %. Therefore, particles from the superhydrophobic surfaces can repeatedly be washed off without a negative efficiency on ESBEC collection efficiency.

In the experiments described above (Figs. 4–6), we focused on optimizing the sampler's performance. Therefore, a commercially-available charger was used and operated separately from the collector, and particle deposition (loss) on the ground electrode of the charging section was disregarded. Taking the results and insights from our testing with the 1st generation ESBEC, we built the 2nd generation ESBEC where a charger is incorporated with the collector as described as shown in Fig. 2. In addition, to improve the uniformity of particle deposition throughout the collector, the 2nd generation ESBEC uses screens with different characteristics (mesh size, wire diameter, and porosity) as shown in Table 1. The performance of the 2nd generation ESBEC, when operated at a flow rate of 105 L/min (7× higher than the 1st gen. prototype) and tested with $0.2 \mu\text{m}$ particles, is shown in Fig. 6. We tested with smaller PSL particles than in our earlier tests because smaller particles are harder to charge and capture (Hinds, 1999). When tested at four different charging and collection voltages ($-9/+9$, $-9/+10$, $-10/+9$, and $-10/+12$ kV), ESBEC yielded collection efficiencies ranging from $75.8 \pm 4.1\%$ to $87.3 \pm 2.0\%$ (Fig. 6a). These results are based on Grimm OPC measurements upstream and downstream of ESBEC. The ESBEC performance at $-9/+9$ kV charging/collection voltage was statistically different (lower) from that at other conditions.

Apparently, increasing charging (or collection) voltage by one kilovolt from the lowest operating condition value improved the collection efficiency by about 12% on an absolute scale; increasing the charging voltage increases the number of electrical charges acquired by particles in the field charging regime (charging section), while a higher collection voltage and stronger resulting electric field ensure more efficient particle capture of charged particles (Hinds, 1999).

The distribution of collected particle mass concentration across the screens also markedly improved as determined by fluorometric measurements (Fig. 6b). Here, the coefficient of variation (COV) of particle mass deposited across the screens was 44%, which was much lower than COV of 120 % observed with the 1st generation ESBEC. The collection efficiencies of the ground screen of the charger section and 1st, 2nd, 3rd, 4th, and 5th screen pairs were 19.4%, 23.3%, 16.4%, 12.1%, 9.2%, and 6.5%, respectively; it yielded a combined collection efficiency of $86.8 \pm 5.1\%$. This particle removal efficiency exceeds California Air Resources Board requirement for Level 3 (best) diesel emission control strategies (Facanha & Ang-Olson, 2008; Shewalla, 2010). Thus, the 2nd gen. ESBEC prototype was operated at an air stream face velocity of 1.5 m/s and yielded collection efficiency approaching 90%. Particle distribution across the screens was also markedly improved.

The ESBEC was successfully developed as a two-stage electrostatic collector with a novel design. Its operation is based on field charging of particles using carbon fiber brush. As part of the collector's development, we have optimized operating conditions (i.e., charging and collection voltages as main factors) and evaluated its performance with particles of different sizes and at different flow rates. These results, combined with an efficient removal of the collected particles simply by washing the screens, show a potential of the proposed technology to remove particles from diesel exhaust with low power consumption, low backpressure and without the need for particle-producing thermal regeneration of the collector. In addition, there are a number of other factors that affect the performance: e.g., composition (or property) of the particle (e.g., diesel particles) and environmental conditions (e.g., temperature and relative humidity) (McLean, 1988; Mizuno, 2000). The next phase of this research will address the collection of actual diesel particles at different mass concentrations and sampling duration. Upon its final development, ESBEC could be used as a stand-alone diesel particulate removal device or in combination with other diesel emission control strategies.

CONCLUSION

A new device to control particle emissions from diesel exhaust has been successfully designed and tested with 0.2 and 1.2 μm PSL particles. Its performance has also been visually verified when challenged with actual diesel emissions. This electrostatic collector with multiple metal screens achieved collection efficiencies close to 90% without a significant pressure drop across the device. Moreover, the screens can be coated with a superhydrophobic substance allowing the removal of the collected particles by simple washing, which eliminates the need for particle-producing thermal regeneration. Thus, the proposed technology exhibits several advantages over conventional DPFs: low backpressure,

low power consumption and easy removal of collected particles by washing. In the continuing work on this project, the ESBEC will be challenged with diesel exhaust at different mass concentrations and for various collection time periods.

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Research Highlights

- An electrostatic collector for diesel exhaust has been designed and tested
- Collector features multiple pairs of screens coated by a superhydrophobic substance
- The collector achieved ~90% particle removal efficiency without a significant pressure drop
- The collected particles can be removed by washing: no without thermal regeneration needed.

The 1st generation of ESBEC

(a) Conceptual diagram:

(b) Prototype: only the collector

Fig. 1.

The schematic representative and a photo of the electrostatic screen battery for emission control (ESBEC). (a) conceptual diagram of the overall structure and basic mechanism, (b) the 1st generation of the prototype.

Fig. 2.

The schematic representative and photos of the 2nd generation of ESBEC. (a) conceptual diagram of the overall structure and basic mechanism, (b) the 2nd generation of the prototype.

Fig. 3.
The schematic diagram of experimental setup.

Fig. 4.

Collection efficiency of the 1st generation of the ESBEC prototype (Fig. 1a) as a function of multiple parameters: a. the number (i.e., 1, 2, 3, and 5 sets) of screen set (24 × 24 mesh screens) at a 0.75-inch gap between each set of screens and 12 V/24 mA charging voltage/current for the commercially-available car ionizer, b. gap (i.e., 0.75 and 1.5 inches) between each set (total 3 sets) of screens (24 × 24 mesh screens) at 12 V/24 mA, c. input current (24 and 50 mA) of ionizer with 3 sets of screens (24 × 24 mesh screens) at a 1.5-inch gap, and d. mesh size of screens (i.e., 0.028 inches in diameter, 44 % aerial porosity, and 24 × 24 mesh size; 0.009 inches in diameter, 30 % aerial porosity, and 100 × 100 mesh size) at two different sets of screens (3 sets: 1.5-inch gap at 12 V/24 mA; 5 sets: 0.75-inch gap at 12 V/50 mA) at 25 L/min sampling flow rates, +7 kV collection high voltage, and 20 min sampling time with 1.2 μm PSL. The error bars represent the standard deviation from three repeats.

Fig. 5.

Collection efficiency of the 1st generation ESBEC prototype using copper screens (i.e., 0.028 inches in diameter, 44 % aerial porosity, and 24×24 mesh size) with 1.2 μm PSL (concentration = $\sim 275 \mu\text{g/m}^3$) at 12 V/50 mA charging voltage/current, +7 kV collection voltage, and 25 L/min sampling flow rates for 7.75 hours sampling time: a) collection distribution on each screen; b) photos of particle deposition on each set of screens (Ground and collection). The error bars represent the standard deviation from three repeats.

Fig. 6.

Collection efficiency of the 2nd generation ESBEC using different sizes of screen set (Table 1) with 0.2 μm PSL at -10/+12 kV charging/collection voltages and at 105 L/min sampling flow rates (i.e. 1.5 m/s face velocity) for 15 min sampling time: a) using different combination of charging/collection voltage; b) collection distribution on each set of screens. The error bars represent the standard deviation from three repeats.

Table 1

Characteristics of mesh screens used for the 2nd generation of ESBECC.

Parameter	Screen Location				
	Charging section		Collection section		
	Ground	1 st pair	2 nd pair	3 rd pair	5 th pair
Fraction of open area (porosity)	0.70	0.70	0.67	0.48	0.47
Mesh size (number of openings/inch)	22	22	24	22	24
Wire width (mm)	0.191	0.191	0.191	0.356	0.356
Opening width (mm)	0.964	0.964	0.868	0.799	0.728
					0.703