

Evaluation of Electrostatic Screen Battery for Emissions Control (ESBEC) with Diesel Emissions

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ABSTRACT

We recently developed a novel diesel emissions control device, Electrostatic Screen Battery for Emissions Control (ESBEC), where diesel exhaust particles are collected onto metal screens using electrostatic principle. This paper focuses on further development of this technology: design and integration of a particle charger and testing of ESBEC with diesel exhaust. Two units - 0.038 and 0.152 m (1.5 and 6 inches) in diameter - were fabricated using 3D printing. Both units feature cylinder-shaped housing integrating the electrical charger and up to seven pairs of metal screens, which collect airborne particles. In the small-scale version, particles are charged by ions emitted from a carbon fiber brush, while in the large-scale version, this is done by using two tungsten wires traversing the cross-section of ESBEC in a crisscross pattern. Small-scale version showed average collection efficiency of 80% over a wide range of diesel exhaust mass concentrations (5 to 400 mg/m³) and 1.5 m/s diesel exhaust face velocity. When ESBEC was tested continuously for 6 hours with diesel exhaust concentration of 300-400 mg/m³, it maintained collection efficiency of >95%. The pressure drop across ESBEC during those six hours increased only minimally. In the next step, the large-scale version was challenged with diesel exhaust of 200 mg/m³ concentration. ESBEC removed 71-99% of exhaust particle mass entering the collector at different temperatures (40-77 °C). In the near future, a full version of ESBEC will be fabricated from a heat-resistant material, and its performance will be compared with a conventional diesel particulate filter.

CITATION: Han, T., Zhen, H., and Mainelis, G., "Evaluation of Electrostatic Screen Battery for Emissions Control (ESBEC) with Diesel Emissions," *SAE Int. J. Engines* 9(4):2016, doi:10.4271/2016-01-9047.

INTRODUCTION

Diesel particulate filters (DPF) have been developed and implemented as a viable option to control diesel particulate matter (DPM) emissions; it is one of the options to retrofit existing diesel engines to control DPM emissions [1, 2, 3, 4]. However, the cost of retrofitting ranges from \$2,500 to \$4,300 per engine (US EPA, 2006) [5]. In addition, the reduction in particle mass concentrations by current DPFs is not consistently accompanied by decreases in the number concentration of ultrafine particles (<100 nm in diameter) [6, 7]. During the operation of a DPF, particles accumulate inside of it and cause an increased resistance to exhaust flow (create backpressure) [8]. Increased backpressure reduces fuel economy and engine performance, thus creating a need to regenerate the DPF by burning off the collected particles [9, 10]. However, in all traditional DPFs, regeneration creates secondary aerosol emission, especially in the 10-30 nm particle size range [11] which contributes to air pollution [12, 13]. There have been attempts to solve these issues by using different DPM collection methods, such as the application of electrostatic precipitation either by itself or in combination with traditional DPFs [14, 15, 16, 17]. However, the presented designs do not offer a viable alternative to existing DPFs and are not commercially available.

In our earlier publication, we presented a novel electrostatics-based DPM collector concept [18], where exhaust particles are electrically charged and then captured onto a series of metal screen pairs by the action of electrostatic forces. This design incorporates various elements from our earlier research: aerosol deposition on screens [19] combined with the development of electrostatic samplers [20, 21, 22, 23]. In our initial development of the collector [24], the incoming particles were electrically charged using a commercially available unipolar car ionizer (AS 150, Wein Products, Inc.). While this charger allowed testing a proof of concept of the collector, it quickly became obvious that it would not be effective when challenged with actual diesel exhaust. Thus, the design of a new particle charger and its integration with the collector was one of the goals of this project.

The developed prototypes Electrostatic Screen Battery for Emissions Control (ESBEC) consist of two main parts: an ionizer for field-induced charging of incoming diesel exhaust particles and a series of metal screen (i.e., mesh) pairs to which a voltage differential is applied to collect the charged particles. This manuscript focuses on the testing and performance of ESBEC prototypes when they are challenged with actual diesel emissions. The prototypes were tested

as a function of charging and collection voltages (8-16 kV), diesel exhaust mass concentration (4-400 mg/m³), exhaust temperature (18-102 °C), diesel exhaust face velocity (0.36-2.1 m/s), and sampling time (3 min to 7 hours). ESBEC's performance was determined in terms of particle collection efficiency and pressure drop across the collector.

MATERIALS AND METHODS

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

Figure 1 shows the schematic diagram and pictures of several ESBEC prototypes. Each is comprised of an electrical charger and a collection section containing multiple pairs of metal mesh screens in series (i.e., a battery of screens) [18, 24]. One screen in each pair is supplied with a high voltage while the other is grounded, thus producing an electrostatic field across the screens. Overall, three different ESBEC models were produced and tested, depending on the objective of a test.

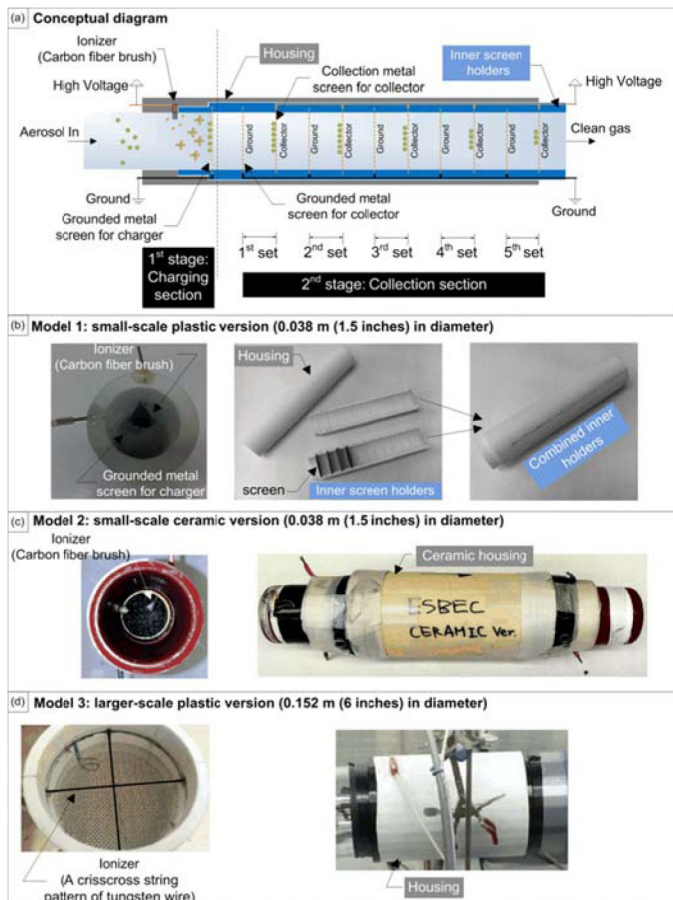


Figure 1. (a) The schematic diagram of the ESBEC, (b) pictures of a small-scale prototype and (c) schematic and pictures of the ionizer section in the large-scale prototype.

Model 1: A Small-Scale ESBEC Model (0.038 m (1.5 Inches) in Diameter) with 7 Pairs of Collection Screens

A new charger utilizing carbon fibers was designed and incorporated with the collector (Figure 1a). Here, an additional screen is positioned in front of the collection section screen and grounded. A carbon brush containing ~800 single carbon fibers of ~7 µm in diameter is positioned in front of that screen at a distance of 0.019 m (0.75 inches) and connected to a high positive voltage. In this design, the carbon brush is located in the outer shell of the device. Once the shell is slid over the collector (two half-cylinder shells holding the screens), the carbon brush is perpendicular to the direction of the airflow and the entire unit is airtight (Figure 1b). Since the carbon brush is connected to a high positive voltage, the voltage used in the collection section is negative. During the ESBEC's operation, the high voltage between the grounded first screen and the tips of the carbon brush creates a strong electrical field which causes ion emission from the brush, and the produced ions attach to the incoming airborne particles. Once the charged particles move further into the battery, the screens connected to the voltage opposite to the sign of their charge attract the particles and remove them from the air stream. The prototype was fabricated by 3D printing technology through www.shapeways.com, and it was made of plastic (e.g., fine polyamide PA 2200). The primary goal of the small-scale model was to verify the performance of the integrated charger and collector when using polystyrene latex (PSL) particles (Duke Scientific Corp.).

Model 2: A Small-Scale, Heat-Resistant ESBEC Model (0.038 m (1.5 Inches) in Diameter) with 2 Pairs of Collection Screens

This model was produced from a heat-resistant and electrically non-conductive material (e.g., ceramic) to investigate ESBEC's performance at high temperatures (e.g., ~93 °C). Since it was a pilot-type test, screen holders for only two pairs of screens were fabricated by 3D printing and then placed into a ceramic housing shell (99.5% AL₂O₃, Ceramic Solution Inc.) (Figure 1c). The rest of the design was the same as in Model 1, i.e., carbon fiber brush charger was used for particle charging.

Model 3: A Large-Scale ESBEC Model (0.152 m (6 Inches) in Diameter) with 7 Pairs of Collection Screens

This model (Figure 1d) was produced using 3D printing to test ESBEC's scalability and ability to handle exhaust flow rates of typical diesel vehicles. The collector's design remained the same as in small-scale models, but the charger was redesigned to ensure that the incoming particles and produced ions are efficiently mixed in the larger air volume. We have explored using different charger configurations: single or four individual carbon brushes and either two tungsten wires or two carbon fiber strings traversing ESBEC in a crisscross pattern. Based on the laboratory experiments with polystyrene latex (PSL) particles (G500B, Duke Scientific Corp.) of 0.5 µm in diameter, we determined that two tungsten strings (76.2 µm in diameter) traversing ESBEC provided the best solution for this ESBEC model (Figure 1d). Here, ions are produced once a voltage differential is applied to the strings and a grounded screen positioned

behind them - the same concept as in the 0.038 m diameter ESBECE - however, the carbon brush is replaced by two tungsten wire strings. The design of the rest of the collector remained unchanged.

Experimental Setup for ESBECE when Testing with Actual Diesel Emissions

The schematic diagram of the experimental setup is shown in Figure 2. It was set up outdoors on the Rutgers University Cook campus in New Brunswick, NJ. It consisted of a diesel particulate matter generator (i.e., source) (Figure 2a), a pipe system for emissions transport, exhaust pipe and flow control valves (brass ball valves, McMaster-Carr Co.) to divert the desired amount of exhaust flow to pass through ESBECE. Depending on the tested ESBECE version (0.038 m in diameter versus 0.152 m in diameter), the pipe adapters were set up accordingly for proper fit (Figures 2b and 2c). A diesel electric generator (6000-watt diesel generator, Central Maine Diesel Inc. operated with no electrical load) was used as a source of diesel particulate matter. A 0.038 m diameter galvanized steel pipe (McMaster-Carr Co.) was used to transport diesel exhaust emissions from the power generator to a split, where a part of the exhaust was diverted to pass through ESBECE while the remaining diesel was exhausted through a pipe 0.102 m (4 inches) in diameter and 3.048 m (10 feet) in height. Figure 2b shows the sampling line for the 0.038 m diameter prototype; it consisted of a dilution airflow blower (model 119104, Ametek, Inc.) with HEPA filter for intake air, a thermocouple thermometer (4015CC, Cole-Parmer LLC), a particle mass monitor (pDR-1200, Thermo Fisher Inc.), a pressure gage, an after-filter and an air mover (e.g., pump). The latter was used to ensure the desired flow rate through ESBECE. A HEPA-filtered dilution airflow provided by the blower was used to adjust the diesel particulate matter concentration ($4\text{--}400\text{ mg/m}^3$); the blower flow rate was controlled by a voltage transformer and a needle valve (both from McMaster-Carr Co.). When testing the 0.152 m ESBECE diameter prototype, diesel exhaust stream was pushed through sampling train by the diesel generator and neither the dilution blower nor the air mover was needed (Figure 2c).

The air flow rate passing through ESBECE was either 25 or 145 L/min for the small-scale model and 660 or 1310 L/min for the large-scale model. The flow rate was measured downstream of ESBECE using a hot wire anemometer (model 9535, TSI Inc.) and adjusted through valve and air blower settings. These flow rates were selected so that the resulting airflow velocities of 0.37–2.1 m/s through ESBECE would be within the range of air velocities in conventional diesel particulate filters. The values are based on a typical range of DPF flow rates ($11\text{--}680\text{ m}^3/\text{hour}$) and diameters (0.12–0.27 m) [25, 26]. Two stable DC high voltage power supplies (205B-10R and 205B-30R, Bertan Associates, Inc.) provided power to the charger and collector of ESBECE; its charging voltage was fixed at +10 kV while its collection voltage was varied from -8 to -16 kV. During ESBECE's operation, the DPM entering the device was positively charged and then collected onto the screens by the electrostatic field between the screens.

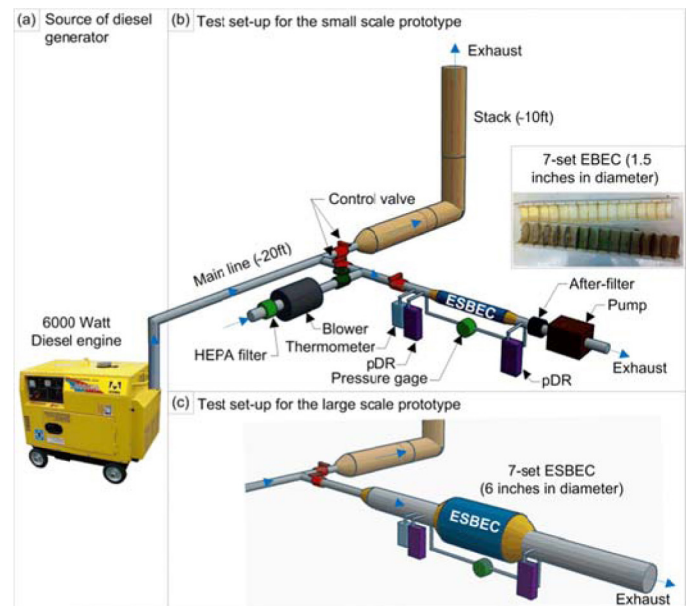


Figure 2. The schematic diagram of the experimental setup: (a) a diesel electrical generator, (b) the sampling line for the small-scale prototype, and (c) the sampling line for the large-scale prototype.

Test Parameters and Determination of ESBECE's Collection Efficiency

The study was structured as three tasks to investigate the field performance of ESBECE with actual diesel emission and, to the extent needed, in the laboratory with PSL particles. Table 1 summarizes the experimental conditions.

Table 1. Summary of experimental conditions used in this study.

Test	Unit	Diameter, m (inches)	Unit material	Flow rate, L/min	Test particles	Pairs of screens
1 st	Small-scale model	0.038 (1.5)	Plastic	25	DPM	7
2 nd	Large-scale model	0.152 (6)	Plastic	1310	0.5 μm PSL	7
				660	DPM	7
3 rd	Heat-resistant small scale	0.038 (1.5)	Ceramic	145	DPM	2

Parameters of the Small-Scale ESBECE

In Test 1, the performance of ESBECE 0.038 m in diameter was tested at three DPM concentrations: low ($< 10\text{ mg/m}^3$), medium ($80\text{--}140\text{ mg/m}^3$), and high ($320\text{--}400\text{ mg/m}^3$) using experimental setup shown in Figure 2b. The airflow rate through ESBECE was 25 L/min (corresponding to 1.5 m/s air face velocity). The DPM concentration upstream and downstream of ESBECE was measured either for 3 min (short-term test) or for up to 6 hours (long-term test). ESBECE was operated at the charging voltage of +10kV while its collection voltage was varied from -8 to -16 kV. Table 2 presents characteristics of