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Effects of Diesel Sulfur Level on the Removal Efficiency of a Small-scale Electrostatic Precipitator

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Ali Farnoud, Chenbo Huang
Graduate Student, Department of Environmental and Civil Engineering, Southern Methodist University, Dallas, Texas

Alfredo Juan Armendariz
Assistant Professor, Environmental and Civil Engineering, Southern Methodist University, PO Box 750340, Dallas, TX, USA, 75275-0340, email: aja@engr.smu.edu

ABSTRACT

Diesel Particulate Matter (DPM), a probable human carcinogen, is one of the largest contributors to ambient PM pollution in urban areas around the world. Emission standards for DPM are becoming more stringent, and likely cannot be met well-into the future with only with modifications to the fuel and engine. The objective of this study was to design and construct an electrostatic precipitator (ESP) to capture DPM from diesel exhaust. A compact laboratory system for the generation, sampling, and analysis of diesel particulate matter was constructed to test the performance of the ESP. DPM was produced by a 6.5 kW diesel-powered electric generator and directed to the ESP through a short section of galvanized steel pipe after the muffler. Mass removal efficiency of the ESP by sampling through a stainless steel cassette and collecting the DPM on Teflon filters. The efficiency was measured while the engine was running idle and at medium load. Two different types of diesel were tested to investigate the effect of fuel type on the efficiency. The results showed that the ESP provides 60-85 percent reductions with both load conditions. The efficiency of the ESP with the engine running on ULSD was between 7 to 18 percent lower than LSD. , the ESP worked with less sparks when ULSD was used.

INTRODUCTION

The year 2008 landmarks the first time in history when more than half of the world's population live in cities, according to the United Nations Population Fund.[1] Air pollution is one of the main problems that each city has to manage in order to reduce the health risk to the habitants. Although governmental agencies try to reduce the emissions by setting strict standards and regulations, a 2007 study on 18 megacities of the world describes the air quality of 13 of them as "poor".[2] This study noted high particulate matter (PM) concentration as a major problem in most cities. Adverse health effects of PM have been addressed by researchers and its removal is highly desired in urban areas.[3-5]

Source apportionment studies show that diesel vehicles contribute the most to the particle pollution problem in cities.[6,7] These vehicles are very efficient and produce a much higher torque compared to gasoline cars. However, high emissions of diesel particulate matter (DPM) restrict their usage for passenger cars. While diesel can be a very attractive source of energy for mining equipments, scientific data on carcinogenicity of DPM convinced states of Ohio, Pennsylvania, and West Virginia to ban diesel engines in their mines.[8]

DPM removal has been a subject of research for decades. Although there have been modifications in the engine and the fuel, recent stringent standards have necessitated some sort of aftertreatment device. Most common aftertreatment suggested so far, has been a combination of diesel oxidation catalyst (DOC) and diesel particulate filter (DPF). DOC converts CO, HC, and soluble organic fraction of DPM into CO_2 and water while DPF captures the carbon core of DPM. Although DOC can successfully convert the majority of harmful gases in the exhaust to harmless CO_2, it is very sensitive to sulfur concentration of the fuel.

The main problem associated with the DOC is the high temperature needed for the activation of the catalysts. DOCs convert SO_2 into SO_3 at temperatures above 300C whereas they need a minimum temperature of 200C to light-off.[9] SO_3 can work as a precursor for nucleation and causes a boost in particle number concentration. In order to facilitate the use of DOCs, EPA introduced Ultra Low Sulfur Diesel (ULSD) regulation in June 2006. However, the use of Low Sulfur Diesel (LSD) is still permitted in stationary, marine, and locomotive diesel engines.[10]

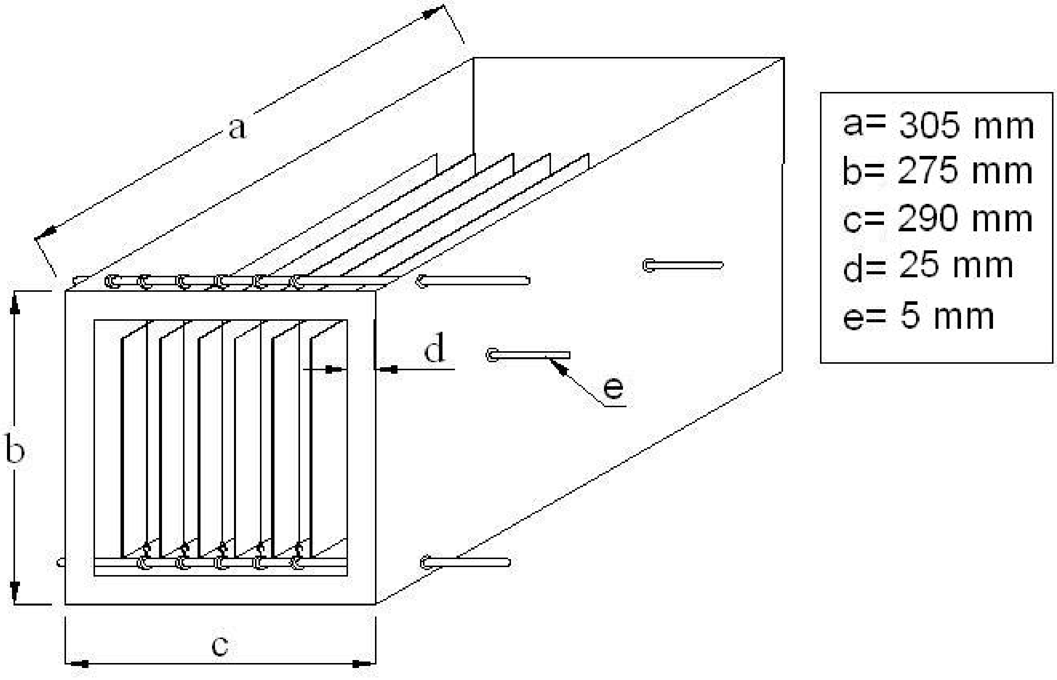
DPFs on the other hand, are very hard to regenerate and have a history of failure during regeneration.[12] Other problems linked with DPFs are very high cost, secondary emissions, and engine backpressure.[13] The objective of this research was to measure the ability of a small-scale electrostatic precipitator (ESP) as an alternative aftertreatment device to remove the DPM from diesel exhaust. The process of testing the ESP on a 6.5kW diesel generator and measuring the efficiency has been described in this paper. Since the change in sulfur concentration affects the conductivity of the exhaust substantially, the ESP was tested under low sulfur diesel (LSD) and ULSD. The tests were performed at two different load conditions to ensure the ability of the ESP to work under different DPM compositions and concentrations.

METHODS

Small-scale prototype ESP

Figure 1 shows a diagram of the small-scale ESP designed and evaluated for this work. The ESP collecting plates were constructed from 1.3 mm (18 gauge) 304 stainless steel. The outer shell was constructed from 3 mm aluminum so that the whole unit would be light but sturdy. The external dimensions were 305 x 275 x 290 mm and the ESP could contain up to seven collection plates with dimensions of 150 x 250 mm. Four 6 mm diameter, 350 mm long aluminum rails were used to support the plates inside the precipitator. 1 mm slits were provided on these rods every 5 mm so that the plate to plate distance could be accurately adjusted. The plates were held in place on the rails with shaft collars and set screws that would tighten on the rails. The rail and shaft collar system enabled easy adjustment of the number and spacing of plates within the ESP. In this study, the distance between the plates was set at 3.5 cm.

Figure 1-Schematic diagram of the ESP



The ESP was designed for up to six rows of wires, and two rows of wire were used for this experiment. Two 5 mm diameter steel rods, 2 cm above and below the collecting plates, were used to hold the wires taut in the ESP. Shaft collars held the ends of each wire and allowed the user to easily change the wire positions. Loops were made and secured on each end of the wire with pin contacts. The loops were attached to hooks on the shaft collars. Experiments were performed with 6-plate/5-wire configurations. Although the tests were run at different plate-to-plate and wire-to-wire distances, in all of the experiments, wires were positioned exactly in the center of the gap between the plates. High-precision calipers (Swiss Precision Instruments, Model 12-529-4, Garden Grove, CA) were used to position the wires. The tests were run using 0.20 mm (0.008 in) stainless steel wires which were approximately 200 mm in length. The diameters of the wires were verified by microscopic filar analysis.

To run the tests over a wide range of voltages and currents, a power supply specifically customized for the ESP was used (Acopian, Model S14159, Easton, PA). The high voltage/AC-input/DC-output power system had a maximum power output of 180 watts and the maximum voltage difference between wire and plate electrodes was 15 kV. Two analog monitors on the power system could measure voltage and current produced. Tests were performed with negative corona with the positive power supply lead connected to the plates. Voltage output from the power supply was adjusted manually by using a knob on the power system. At each plate-to-plate distance, the tests were run at a minimum of three different voltages: one close to the corona onset voltage, another close to sparkover voltage, and one or two tests in between these two voltages. Insulating mylar sheets were used on several internal ESP surfaces for safety reasons to insure that random sparking and/or induced charging from the electrodes did not energize the ESP shell.

Experimental setup

The setup for the DPM generation, sampling, and analysis system is shown in Figures 2 and 3. A 6.5 kW diesel generator produced diesel exhaust (Duropower, model DP6500DES) and there were two primary lines of one inch galvanized steel pipe to transport the exhaust from the engine to the sampling lines and ventilation hoods. Two ball valves were used to adjust the flow that went through each line and the flow rate of the main line was measured using an orifice plate and a manometer. The sampling line was made from quarter inch stainless steel tubing which was introduced into the main line at an elbow, as shown in Figure 1. The sampling line was inserted 10 centimeters into the main line and parallel to the pipe walls. A needle-valve controlled the amount of flow directed into the sampling line. The sampling line flow was metered by a laboratory-made venturi meter before going to the dilution system.

Experiments were performed with diesel particles generated at two different loads: idle and medium load. The medium load tests were performed with four 500 watt lamps connected to the generator, drawing approximately 30 percent of the engine's rated power. Initial experiments showed that the engine needs to be warmed up for at least 60-90 minutes before the experiments to assure a fairly consistent concentration of particles. Evaluating the removal efficiency of the ESP is rather difficult when particle concentration fluctuates. The experiments were also performed with two different types of diesel fuel: LSD and ULSD. The LSD used in the experiments was analyzed in the laboratory and had an average sulfur concentration of 550ppm. Due to very low sulfur concentration of ULSD, it was not analyzed but the standard allows a maximum concentration of 15ppm.

Figure 2. Exhaust transfer from the diesel generator to the hood

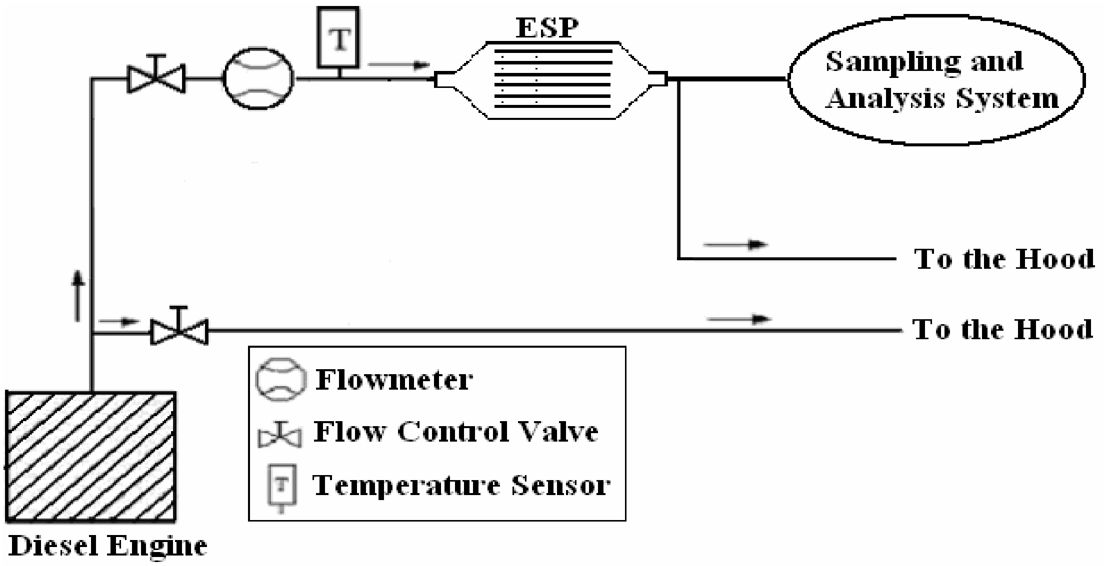
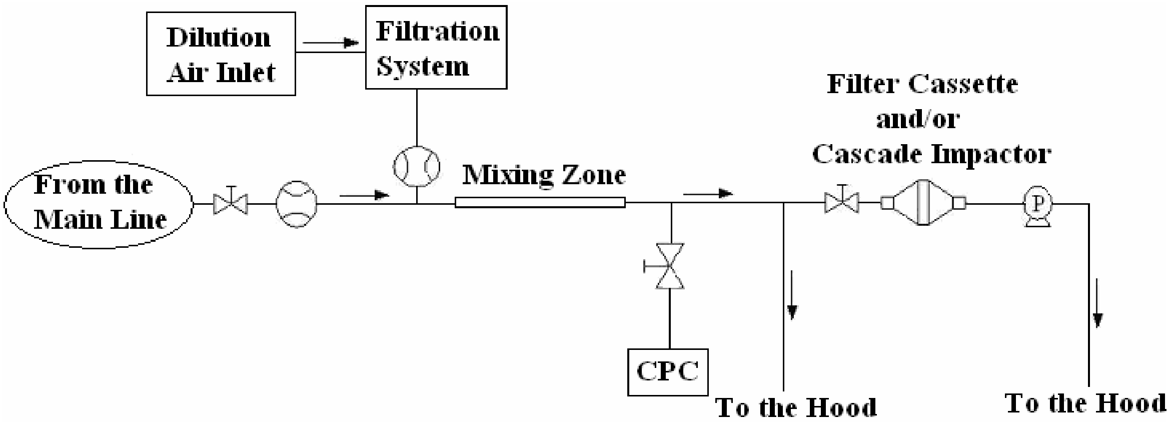


Figure 3. Sampling and analysis system for measuring mass concentration, number concentration, and size distribution.



Mass removal efficiency tests

Mass concentration measurements were performed by sampling diesel exhaust through pre-weighed 47 mm Teflon membrane filters held in a stainless steel cassette. Exhaust was sampled for each test for at least 10 to 20 minutes. The mass gained in the filter was divided by the volume of exhaust sampled to obtain mass concentration. Teflon membrane filters (Pallflex Membrane T60A20, East Hills, New York) were used for this experiment and allowed for high efficiency collection and consistent flow rate during sampling. All filters used in the filter cassette and cascade impactor were weighed with a calibrated microbalance (Perkin Elmer, AD-6 Auto balance, Waltham, MA). The filters were baked for six hours after each test and the mass of the non-volatile part of DPM was reported and used in calculating mass concentration.

At each engine load and ESP power supply setting, at least three tests were performed to determine ESP collection efficiency. Using the knob on the power supply, the voltage changed and the removal efficiency was measured at different voltages. The result was efficiency vs. voltage curve which was used to describe the best voltage to operate the ESP. At each voltage, the mass concentration of the exhaust was measured for at least 10 minutes, first with the ESP off and then with the ESP on. The removal efficiency was then calculated with the following equation:

$$E = \frac{C_{off} - C_{on}}{C_{off}} \tag{3.1}$$

Where:
E=mass removal efficiency of the ESP
C_{off}=mass concentration of the ESP with the power supply off
C_{on}=mass concentration of the ESP with the power supply on.

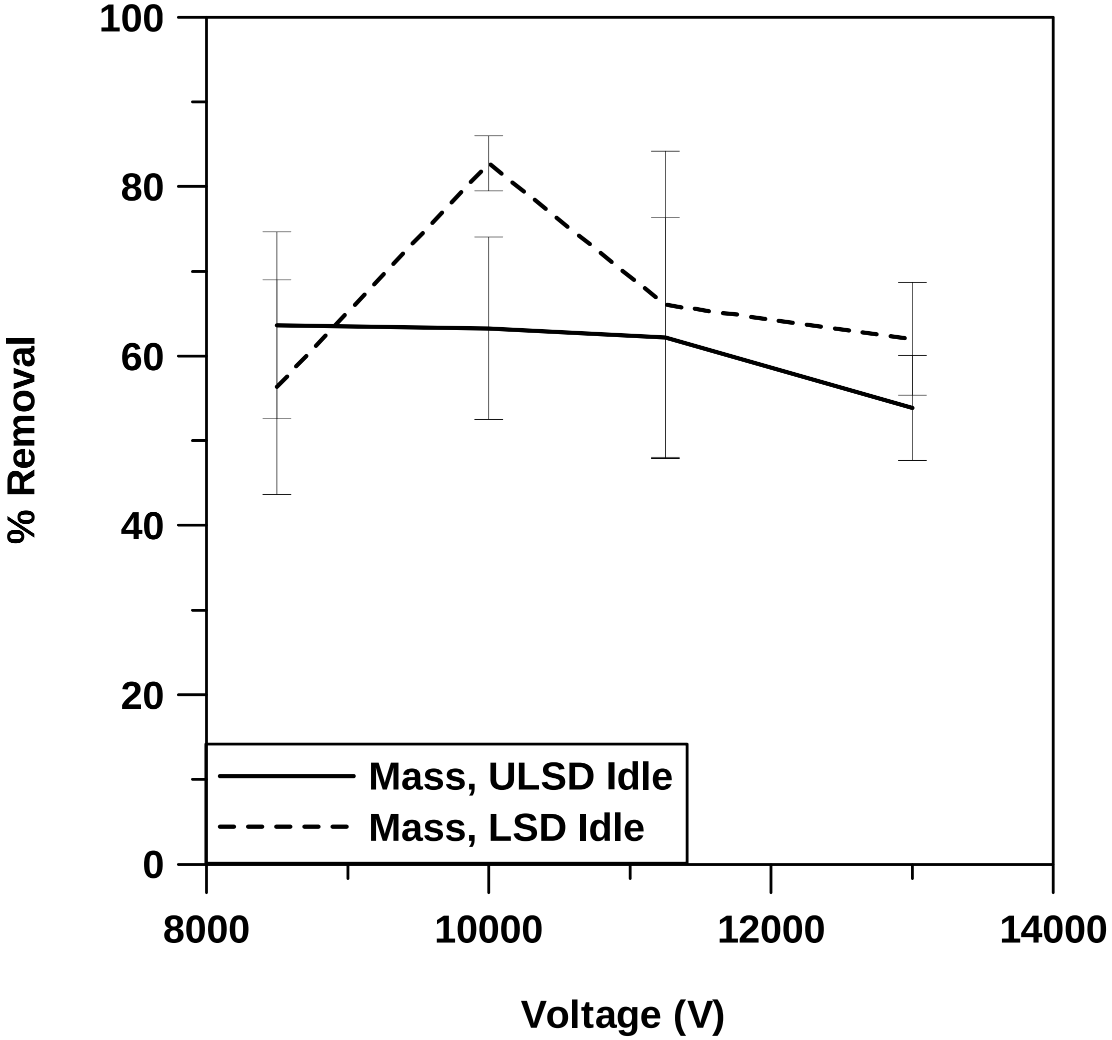
DATA AND DISCUSSION

Engine running idle

The first set of experiments was performed with the engine running on idle. Figure 4 shows the effect of fuel type on the removal efficiency of the ESP when there is no load on the engine. The figure shows that when the engine is running on LSD, there is a clear peak at 10,000 volts where the removal efficiency is around 85 percent. The decrease in the efficiency at voltages above 10,000 volts is due to the intermittent sparking of the ESP. Although the ESP produces more current at higher voltages which can trap more of the particles, the intermittent sparking returns the particles to the flow. In addition, the corona vanishes for a fraction of a second after each spark and as a result, the exhaust leaves the ESP untreated. Operating the ESP at voltage above 13,000 volts was very difficult due to extensive sparking. In addition to the high current, the wires shake vigorously at higher voltages and increase the probability of sparking.

When the engine ran on ULSD, the resulted voltage-efficiency curve was considerably different from that of LSD. First, there was no clear peak in removal efficiency curve and the ESP was running constantly with an efficiency of 65 percent over a large span of voltages. Secondly, the decline in the curve happened only when the ESP was running at 13,000 volts. It appears that sulfur concentration is the reason for such difference. SO_2 molecules have a high electron affinity which creates a much more conductive medium for the current to pass through.[14] Consequently, sparking only occurs at higher voltages resulting in less intermittent sparking when ULSD is the source of energy. However, mass removal efficiency is on average 7 percent lower for ULSD as a result of lower conductivity of the medium.

Figure 4. The effect of fuel type on the mass removal efficiency of the ESP when the engine is running idle.



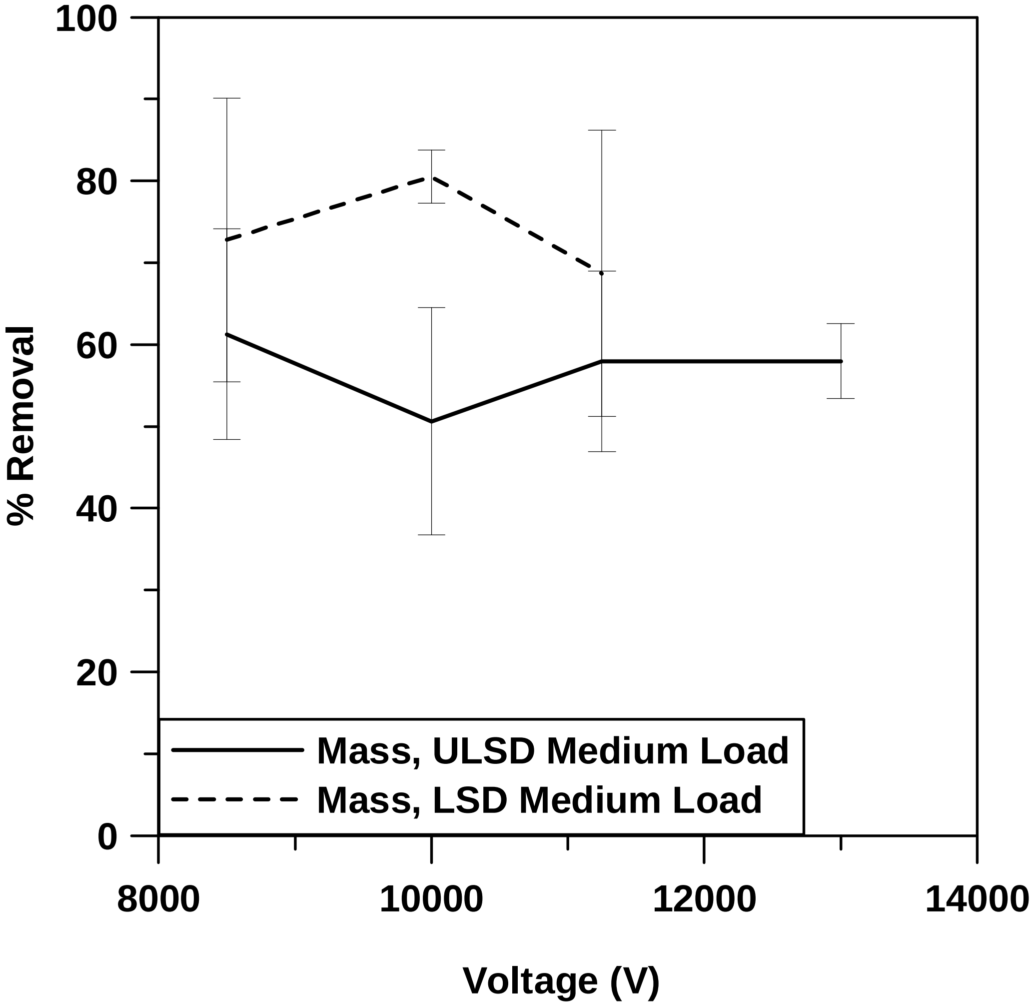
Medium load experiments

Tests were performed to measure the efficiency of the ESP with the engine working at medium load and samples were taken from the engine while it was working at 30 percent of its rated power. Figure 5 shows the effects of fuel type on efficiency-voltage curves. Like the idle engine experiments, there was a clear peak at 10,000 volts when the engine was running on LSD. The efficiency quickly decreased and extensive sparking impeded the operation of the ESP at 13,000 volts. Therefore, the removal efficiency of the ESP could not be measured at 13,000 volts. The reason for this extensive sparking has to do with conductivity of the medium again. Putting load on the engine increases the temperature of the engine and changes the structure of DPM. High temperature works in favor of elemental carbon and increases its share in the structure of DPM, making the particle more conductive. This effect combined with high sulfur concentration will reduce the sparkover voltage of the ESP and it cannot be run at voltages above 12,000 v.

ULSD efficiency-voltage curve was not significantly different from the ULSD curve in figure 4. Although there was a drop at 10,000 volts, the values were mostly around 60 percent. However, the average efficiency of the ESP was around 18 percent lower for ULSD. Although the experiments can be performed for even higher voltages for ULSD, the power consumption of the ESP was relatively high at voltages above 13,000 volts. As a result, 13,000 volts was adopted as higher voltage limit in the experiment.

The average power consumption of the unit varied between 10 to 30 watts depending on the operating voltage. Power consumption for treating the exhaust of an average diesel passenger car was predicted to be around 80-120 watts. This power consumption is comparable to stereo systems and can be drawn from the car electrical system. Also, the average size of the unit, if used on average passenger cars, was predicted to be around 1ft^3 which is comparable to the particulate removal systems currently used. Reasonable power consumption and size, justify further research on small-scale electrostatic precipitators for diesel particulate removal.

Figure 5. The effect of fuel type on the mass removal efficiency of the ESP. Medium load on the engine.



CONCLUSION

A small-scale ESP was designed, built, and tested to remove DPM from diesel exhaust. A diesel-powered electric generator was used to generate the diesel exhaust, at both idle and medium load conditions. Low-Sulfur diesel with a sulfur concentration of 550ppm and Ultra Low Sulfur Diesel with a sulfur concentration lower than 15 ppm were used in the experiments. The mass removal efficiency of the ESP was obtained at different load conditions and the effect of fuel type on the removal efficiency was investigated. The ESP removed up to 85 percent of the mass in LSD case and up to 65 percent of the mass for ULSD. On average, mass removal efficiency of the ESP was 7 percent lower for idle and 18 percent lower for medium load when the engine was running on ULSD. However, the ESP worked with less sparks when ULSD was used. Future work will focus on improving the current design, including scaling up to larger engines and developing a regeneration system to bring it closer to road testing and commercialization.

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