Performance and analysis of retrofit electrostatic precipitator before diesel particulate filter to reduce particulate matter in diesel exhaust system

Article *in* International Journal of Ambient Energy · March 2019

DOI: 10.1080/01430750.2019.1594374

Sathish Saravanan
Hindustan University

International Journal of Ambient Energy

ISSN: 0143-0750 (Print) 2162-8246 (Online) Journal homepage: https://www.tandfonline.com/loi/taen20

Performance and analysis of a retrofit electrostatic precipitator before a diesel particulate filter to reduce particulate matter in diesel exhaust system

Johnson Samuel, S. Sathish & M. Parthiban

INTERNATIONAL JOURNAL OF AMBIENT ENERGY
https://doi.org/10.1080/01430750.2019.1594374

Taylor & Francis
Taylor & Francis Group

Check for updates

Performance and analysis of a retrofit electrostatic precipitator before a diesel particulate filter to reduce particulate matter in diesel exhaust system

Johnson Samuel[a], S. Sathish [a] and M. Parthiban[b]

[a]Department of Mechanical, Hindustan Institute of Science of technology, Chennai, Tamil Nadu; [b]Department of Mechanical, Vels Institute of Science of technology, Chennai, Tamil Nadu

ABSTRACT

In this work, an electrostatic precipitator is used in a diesel particulate filter to reduce the particulate matter (PM) emission and lead emissions. As evident by the USEPA (United States Environmental Protection Agency), the trucks and buses account for one-fourth of PM and one-third of lead suspended in the atmosphere. The diesel particulate filter, as an individual, has its own limitation, that is, only ultra-low sulphur diesel must be used (15 ppm); otherwise, the particulate filter clogs and engine exhaust back pressure increases leading to engine failure. Electrostatic precipitator is found to have some drawback from the research: it cannot precipitate the low resistive diesel PM in its collection plates. The concurrent use of these two helps in overcoming the above-mentioned problems. Other than this, the use of this set-up has decreased in the rate of increase in back pressure at the exhaust system. The particle number density is 98% less when compared to a system of diesel particulate filter only. It increases the collection efficiency of PM and engine efficiency.

ARTICLE HISTORY
Received 11 January 2019
Accepted 6 March 2019

KEYWORDS
Diesel particulate filter; electrostatic precipitator; particulate matter

1. Introduction

The fine particles (particles less than 10 µm) of diesel engine emission (known as particulate matter, PM) cause serious health problems (Van Setten, Makkee, and Moulijn 2001). They can penetrate the alveolus in our lungs causing premature mortality, aggravated asthma, etc. It is likely a carcinogen and in addition, the PM from diesel exhaust system contributes to acid rain, smog and global climatic change to the world. So, more effective emission norms are posed by the government. Bharat stage norms are the standards instituted by the government in 2000 to regulate emissions, air pollutants from motor vehicles. With appropriate fuel and technology, they limit the release of air pollutants such as nitrogen oxides, carbon monoxide, hydrocarbons, PM and sulphur oxides from vehicles using internal combustion engines. As the stage goes up, the control on emissions becomes stricter. Thus Bharat stage VI norms are two stages ahead of the euro norms; we have included the emission norms of different EU emission norms like Europe reported (Sathish and Shiva 2016) (Table 1).

The EU Emission Standards for HD diesel engines, g/kWh (smoke in m^{-1}) for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000/min. EEV is 'enhanced environment-friendly vehicle'. In the future, more regulations and norms will be implemented to maintain the emissions.

2. Principle of working

2.1. Electrostatic precipitator

It works on the principle of electrostatic charging or corona discharging that is when a negatively charged high voltage is passed through the discharging electrode, the fast-moving electrons bump the gas molecules near to the discharging electrode, so positive ions and free electrons are evolved. The positive gas ions are taken back by the discharge, whereas a free electron produces negative gas ions. When a PM enters the electrostatic precipitator, the gas ions stick to the particles, imparting a negative charge to them. The suspended PM gets agglomerated and becomes heavier and larger particles. The gas ions carry away the agglomerated particles to the collection plate suggested (Saiyasitpanich et al. 2006).

2.1.1. Diesel particulate filter

It works on the principle of mechanical filtration; just as a sieve it is used to clean the floor. The emission is passed through microstructural fibres. The large PM gets entrapped in the porous media. As per USEPA, a diesel particulate filter is defined as a ceramic device that collects the PM in the exhaust stream. The high temperature of the exhaust heats the ceramic structure and allows the particles inside to break down (oxidise) into less harmful components (Saiyasitpanich et al. 2006).

CONTACT S. Sathish sathishamg88@gmail.com

Table 1. Euro emission norms for heavy-duty diesel engines.

Tier	Date	Test cycle	CO	HC	NOx	PM
Euro I	1992 < 85KW	ECE R-49	4.5	1.1	8.0	0.612
	1992 > 85KW		4.5	1.1	8.0	0.36
Euro II	October 1996		4.0	1.1	7.0	0.25
	October 1998		4.0	1.1	7.0	0.15
Euro III	October 1998 EEV'S only	ESC & ELR	1.0	0.25	2.0	0.02
	October 2000	ESC & ELR	2.1	0.66	5.0	0.10
						0.13
Euro IV	October 2005		1.5	0.46	3.5	0.02
Euro V	October 2018		1.5	0.46	2.0	0.02
Euro VI	January 2013		1.5	0.13	0.4	0.01

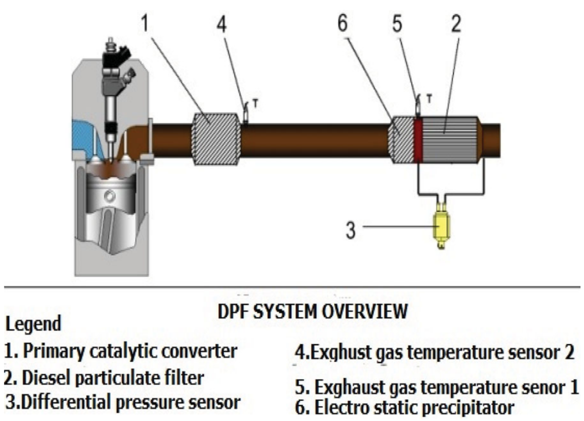

Figure 1. The overview of the modified system where an electrostatic precipitator is placed before a diesel particulate filter.

3. The need for retrofit

An electrostatic precipitator is a leading technology used in the exhaust system, but it is currently limited to application for factories. But an electrostatic precipitator cannot be used as an individual in the treatment of flue gas from diesel engines. It is because of the abnormal re-entrainment of the PM from the collection plate, which is due to low resistive nature of the PM (particulate matter).

Even though a diesel particulate filter is mandatory for a diesel engine (according to emission norms), it is used in all diesel vehicles, under the following conditions.

- Only ultra-low sulphur diesel – low sulphur diesel ranging from ∼10 ppm of sulphur to ∼50 ppm of sulphur; otherwise, the PM from the fuel clogs the DIESEL PARTICULATE FILTER leading to increased back exhaust back – pressure and engine damage.
- 'Filter regeneration' occurs only at high speed (64 km/h) which is not suitable for urban vehicles.

4. Modified system

This combined system is placed after the catalytic converter. Temperature and pressure sensors are installed to note readings (Figure 1).

Figure 2 illustrates that the discharge electrode is energised with a negative DC high voltage. A grounded stainless steel tube

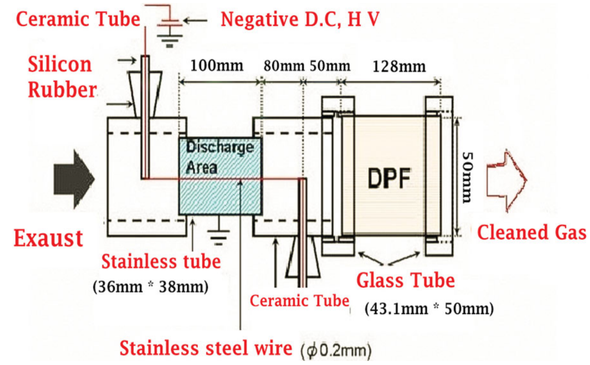

Figure 2. A modified system of an electrostatic precipitator and a diesel particulate filter.

acts as the collection plate even though it shows minimal entrapment of PM. It is kept to reduce the burden of diesel particulate filter.

Corona discharge is onset at −6 kv and to increase the efficiency the voltage is increased up to −12 kv (current – 0.5–1.2 mA). An EEPS (engine exhaust particle sizer) is used to measure the particle density emitted (Di Natale and Carotenuto 2015).

5. Results and discussion

To calculate the collection area with our assumed efficiency:

To find the critical ionic charge:

Critical ionic charge $q_c = 12\pi\varepsilon_o R^2 E_a \varepsilon_o$

where

$E_a =$ field intensity in the neighbourhood of the PM

$R =$ radius of an ion

$\varepsilon_o =$ particle surface area

$q_c = 12\pi\ (8.85 \times 10^{-12})\ (0.5 \times 10^{-6})^2\ (2 \times 10^5)$

Assuming

Radius $R = 0.5\,\mu$m

$E_a = 2 \times 10^5$

Therefore, $q_c = 1.7 \times 10^{-7}$ C

Mobility $\mu = q_c / 6\pi\tau$ R

where

$\tau =$ viscosity of air inside electrostatic precipitator.

$$= \frac{1.7 \times 10^{-7}}{6\pi \times (1.804 \times 10^{-7})(0.5 \times 10^{-6})}$$

$$= \frac{1.7 \times 10^{-7}}{1.7 \times 10^{-10}}$$

$$= 10^{-7}$$

Migration velocity, $w = \mu E_a$

$$= 10^{-7}(2 \times 10^5)$$

$$= 2\ \text{cm/s}$$

$$W = 0.02\ \text{m/s}$$

Other calculation is performed using Mahindra powerol 4-stroke 6-cylinder. Inline direct injection diesel engine's output power is 40 kW = 53.98 Hp

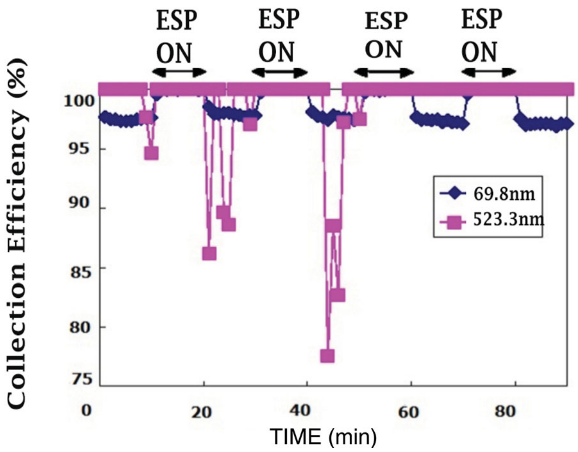

Figure 3. Collection efficiency increases up to 99.9% when the electrostatic precipitator is powered on.

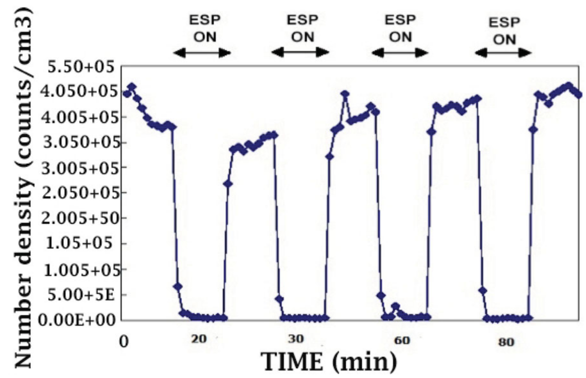

Figure 4. Graph showing the decrease in PM when the electrostatic precipitator is switched on.

$\tau = 1-e^{-W}$ (A/Q)

Which is called a Deutsch–Anderson equation where (DEUTSH, w .1992 *Annals of Physics* 68:335)[5]

$\eta =$ efficiency of the electrostatic precipitator

$A =$ collection in m^2

$Q =$ gas flow rate m^3/s

$W =$ migration velocity m/s

For the Mahindra powerol 40 kW diesel engine gas flow rate = 0.155 l/min

Converting l/min into m^3/s

$Q = 2.583 \times 10^{-6}\ m^3/s$

On the Deutsch–Anderson equation, let us assume the efficiency to be 99.5%

Then,

$$A = (-Q/w)(\ln[1-\eta])$$

$$= \frac{-2.583 \times 10^{-6}}{0.02} \quad [\ln(1-0.9950)]$$

$$A = 6.843 \times 10^{-4} m^2$$

But the assumptions on the calculations for *w* [Migration velocity] are made from static gas analysis.

Let us decrease the migration velocity by 50% to compensate the loss during flow so, $w = 0.01$ m/s.

$$A = \frac{-2.583 \times 10^{-6}}{0.01}[\ln(1-0.9950)]$$

$$A = 1.369 \times 10^{-3} m^2 \quad \text{which is probable and practical in an exhaust system}$$

6. Advantages of modified system

The graph given below gives a clear note that the particle collection efficiency is increased with the concurrent technology of electrostatic precipitator and diesel particulate filter.

The collection efficiency increases up to 100% for particles as large as 523.3 nm and above 98.5% or 99.5% for particles at a size of 69.8 nm as shown in Figure 3.

From references, it is found that, if the number density is 17,500,000 counts/cm^3 at the inlet the collection efficiency of

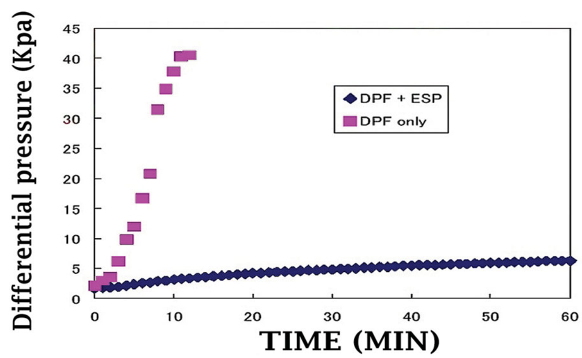

Figure 5. Exhaust back pressure increases abruptly with the installation of particulate filter only.

diesel particulate filter was about 98% indicating that about 350,000–450,000 counts/cm^3 at the outlet shown in Figure 4. When an electrostatic precipitator + diesel particulate filter system is used, the counts decrease sharply to almost negligible amounts of 2000–7000 counts/cm^3, resulting in a collection efficiency of 99.9%. The graph in Figure 4 shows the ability of this concurrent technology. This might be seen due to ease in catching of agglomerated particles by the diesel particulate filter (Yao et al. 2009).

6.1. Advantage

There is a minimal increase in the exhaust back pressure. As shown in Figure 5, without electrostatic precipitator operation, the pressure increased to 35 kpa in 9 min. In this retro fit, it increased significantly slower. As the exhaust back pressure increase is responsible for the decrease in the efficiency of the diesel engine, the decrease in back pressure is considered a best advantage for the concurrent use of electrostatic precipitator and diesel particulate filter (Neeft, Makkee, and Moulijn 1996).

Firstly, this might be due to the entrapment of particles in the collection tube. Secondly, the observation of the diesel particulate filter through the scanning electron microscope (SEM) reveals that the formation of pearl chain-like structure in the diesel particulate filter fibres leading to decreased clogging.

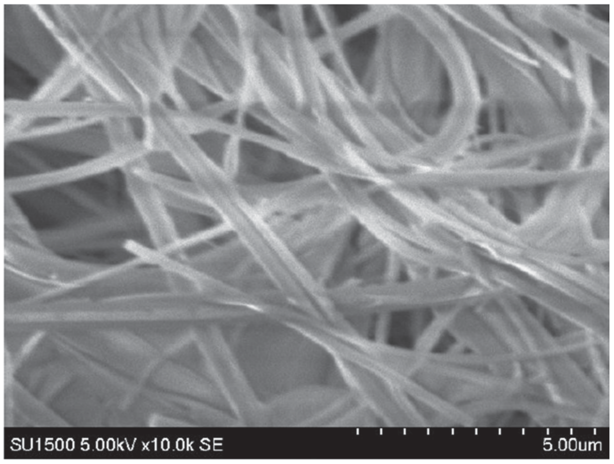

Figure 6. Clean fibres before the test fitting in the exhaust system.

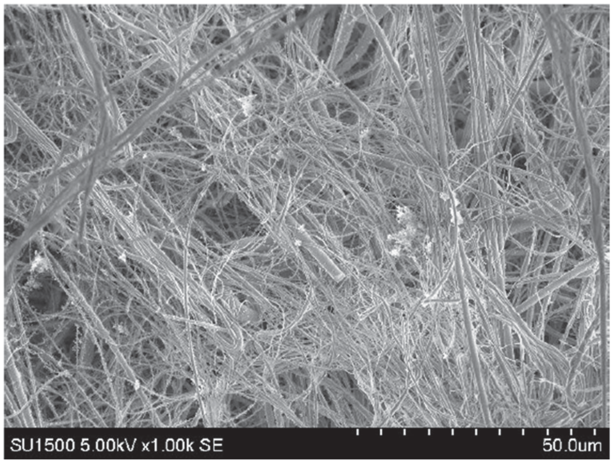

Figure 7. Round masses seen in the fibres.

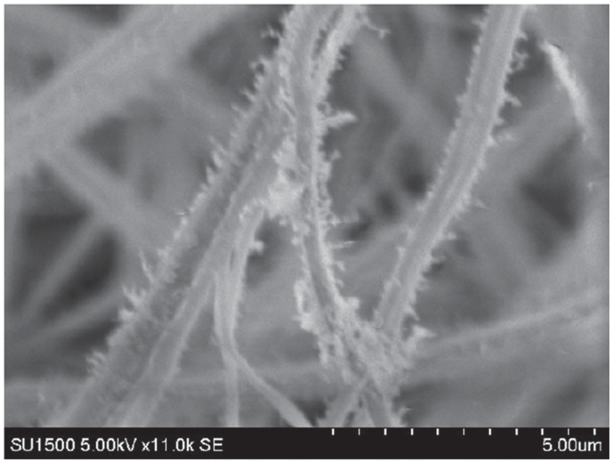

Figure 8. This graph shows hair-like or pearl chain-like structures over the fibres – the cause for reduced differential pressure.

7. Comparison of SEM results

It is clear from the SEM images that the PM sticks to the fibres of the diesel particulate filter in round masses which causes clogging (Schmeichel 2007). But the hair-like formation of PM is

Figure 9. Much more magnified image of SEM.

found in the images taken after fitting an electrostatic precipitator before the diesel particulate filter; this leads to reduced clogging in turn leading to decreased exhaust back pressure (Figures 6–9) .

This pearl chain-like structure is formed due to the electrostatic charging prior to filtration by the diesel particulate filter.

8. Conclusion

(1) The combination of electrostatic precipitator + diesel particulate filter is efficient enough to meet the stringent norms in the near future and outlet of the exhaust system is comparatively and significantly reduced.(98% less compared to diesel particulate filter only)
(2) The exhaust back pressure increased gradually after a long time when compared to diesel particulate filter only. This, in turn, increases the engine efficiency.
(3) Hence, the filter in the diesel particulate filter can be regenerated and changed after longer intervals leading this retro fit into a cost-efficient technology (Kim et al. 2010).

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

S. Sathish http://orcid.org/0000-0003-4969-419X

References

Di Natale, Francesco, and Claudia Carotenuto. 2015. "Particulate Matter in Marine Diesel Engines Exhausts: Emissions and Control Strategies." *Transportation Research Part D: Transport and Environment* 40: 166–191.

Kim, H. J., B. Han, W. S. Hong, W. H. Shin, G. B. Cho, Y. K. Lee, and Y. J. Kim. 2010. "Development of Electrostatic Diesel Particulate Matter Filtration Systems Combined with a Metallic Flow-Through Filter and Electrostatic Methods." *International Journal of Automotive Technology* 11 (4): 447–453.

Neeft, John P. A., M. Makkee, and J. A. Moulijn. 1996. "Diesel Particulate Emission Control." *Fuel Processing Technology* 47 (1): 1–69.

Saiyasitpanich, Phirun, T. C. Keener, M. Lu, S. J. Khang, D. E. Evans. 2006. "Collection of Ultrafine Diesel Particulate Matter (DPM) in Cylindrical Single-Stage wet Electrostatic Precipitators." *Environmental Science & Technology* 40 (24): 7890–7895.

Sathish, Vivekanandan., and Shanmugam Siva. 2016. "Parametric optimization for floating drum anaerobic bio-digester using Response Surface Methodology and Artificial Neural Network." *Alexandria Engineering Journal* 55 (4): 3297–3307. https://doi.org/10.1016/j.aej.2016.08.010.

Schmeichel, Steve D. 2007. Apparatus for Emissions Control, System, and Methods. U.S. Patent No. 7,278,259, 9 October.

Van Setten, Barry A. A. L., Michiel Makkee, and Jacob A. Moulijn. 2001. "Science and Technology of Catalytic Diesel Particulate Filters." *Catalysis Reviews* 43 (4): 489–564.

Yao, Qiang, S.-Q. Li,H.-W. Xu, J.-K. Zhuo, and Q. Song 2009. "Studies on Formation and Control of Combustion Particulate Matter in China: A Review." *Energy* 34 (9): 1296–1309.