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POWERTRAP: ULTRAFINE PM CONTROL WITHOUT PERFORMANCE PENALTIES

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ABSTRACT

The PowerTrap^{TM} ?is a non-exhaust temperature dependent system that cannot become blocked and features a controlled regeneration process independent of the vehicle's drive cycle. The system has a low direct-current power source requirement available in both 12-volt and 24-volt configurations. The system is fully programmable, fully automated and includes Euro IV requirements of operation verification. The system has gained European component-type approval and has been tested with both on- road and off-road diesel fuel up to 2000 parts per million.

The device is fail-safe: in the event of a device malfunction, it cannot affect the engine's performance. Accumulated mileage testing is in excess of 640,000 miles to date. Vehicles include London-type taxicabs (Euro 1 and 2), emergency service fire engines (Euro 1, 2, and 3), inner city buses, and light-duty locomotives. Independent test results by Shell Global Solutions have consistently demonstrated 85- 99 percent reduction of ultrafines across the 7-35 nanometer size range using a scanning mobility particle sizer with both ultra-low sulfur diesel and off-road high-sulfur fuel.

INTRODUCTION

The negative health and environmental effects of diesel particulate emissions are well known and well documented [1, 2, 3]. The resultant forthcoming strict emissions regulations are forcing vehicle manufacturers and operators to consider diesel particulate filters (DPFs) as standard equipment due to the realization that the necessary emissions targets will not be met through improvements in engine design alone [4].

The most common approach to DPF usage is to filter the entire exhaust gas stream of a vehicle with a ceramic monolith wall flow filter [5]. This method has been proven to achieve significant reductions in emitted particulate matter but requires periodic regeneration of the filter medium in order to remove the deposited particulate matter. The particulate matter must be removed in order to reduce the restriction on the exhaust gas flow which can introduce a performance penalty to vehicle operation.

DPF regeneration is carried out by incineration of the deposited particulate matter which requires a temperature of around 600^{o}C (unaided). Temperatures of this magnitude are seldom reached in the majority of diesel vehicle exhausts. A common approach is therefore to catalyze the filter medium so that particulate oxidation occurs at a lower exhaust gas temperature. Other approaches include the use of a fuel borne catalyst or the creation of reactive oxidants. However, catalyst development has only succeeded in reducing the particulate oxidation temperature to around 320^{o}C [6]. The use of reactive oxidants can achieve regeneration at exhaust temperatures as low as 275^{o}C if the vehicle is run on low sulfur diesel fuel [7]. Therefore, these temperature requirements mean that these technologies are unsuitable for use in light duty, low exhaust gas temperature applications such as inner city taxi vehicles or light duty commercials. Increasing inner city congestion means that a vehicle spends more time idling at low exhaust gas temperatures.

THE TECHNOLOGY

Per-Tec Ltd has developed a novel approach to diesel particulate reduction based upon the principles of electrostatic precipitation, a pollution reduction technique which has been used in large scale industrial applications for over a century [8,9].

Figure 1 gives a brief overview of the functioning of the device. The exhaust gas is ionized by corona discharge (A) as it passes a high voltage electrode centrally mounted within a section of exhaust tube (the field tube). This results in the formation of charged particulates which are repelled by the HV electrode to the inner surface of the field tube where agglomeration takes place (B).

This process results in the formation of a concentration gradient of particulate across the exhaust flow. A secondary concentrated particle stream is then created which is handled by an electrically regenerative particle filter. This secondary gas stream is typically around 10% of the whole exhaust gas. The majority of the cleaned exhaust gas flows around the filter.

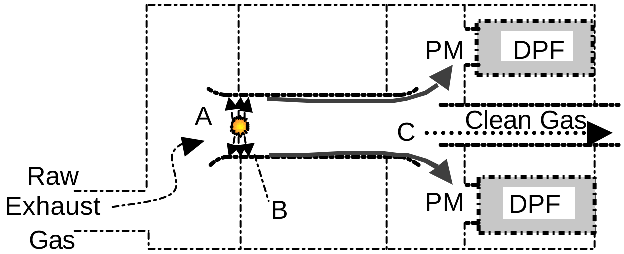

Figure 1 – Schematic of Novel Electrostatic Aftertreatment Device

The electrostatic particle ionization and manipulation processes are discussed in more detail in an earlier paper [10]. The use of electrostatic particle treatment in conjunction with an electrically regenerative filter possesses a number of key benefits which will now be discussed in more detail.

Non-Temperature Dependence

The PowerTrap is non exhaust temperature dependant technology. The filter in the DPM reduction device is heated electrically. As a result, regeneration can be carried out at any exhaust gas temperature. The development of a remote data acquisition system [11] has allowed the performance of this technology to be monitored in real time on a number of different vehicles. Figure 2 shows the temperature curve from a filter regeneration carried out on a 2.5 ltr taxi vehicle fitted with the DPM reduction device. As can be seen, the filter reaches approximately 600^{o}C in 2 minutes whilst the pre-device exhaust gas temperature remains at approximately 150^{o}C.

Rapid regeneration is facilitated by the reduced cooling effect of the exhaust gas. The fact that only a small portion of the total exhaust flow passes through the filter means that the cooling effect on the filter is minimized.

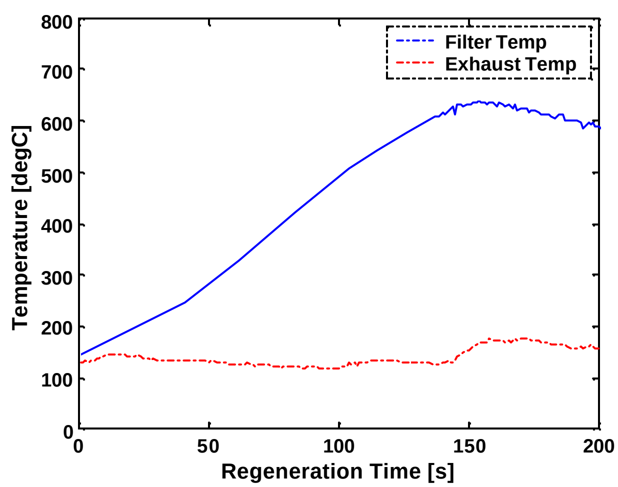

Figure 2 – Low Exhaust Temperature DPF Regeneration on 2.5ltr Taxi Vehicle

Figure 3 shows the speed / time curve during the filter regeneration process on the taxi. The vehicle speed fluctuation shows similar characteristics to the European Union ECE drive cycle which is commonly used for emissions certification. During the regeneration, the vehicle was most probably starting and stopping at traffic signals or in heavy traffic.

Figure 4 represents exhaust gas temperature data collected from the same taxi operating in and around Manchester City Centre. The graph shows the proportion of total time that the exhaust gas is above a certain level and the data was recorded over a 12-hour period of vehicle operation. As can be seen the exhaust gas temperature seldom exceeds 250^{o}C. This proves the ability of this technology to work at low exhaust gas temperatures.

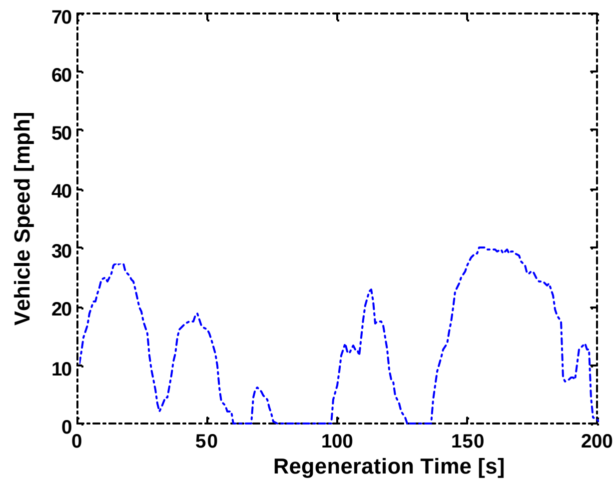

Figure 3 - Speed vs. Time during Filter Regeneration on 2.5l Metrocab Taxi Vehicle

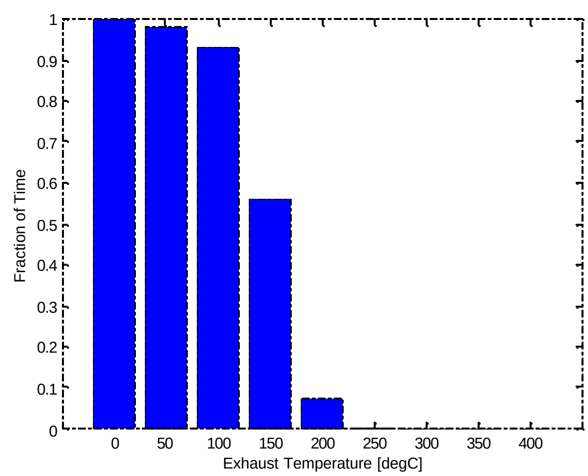

Figure 4 - Exhaust Temperature Profile for 2.5 ltr Metrocab

The Device is Non-Blocking

The fact that only a small portion of the entire exhaust gas stream is handled by the filter and the majority of the exhaust gas flows around the filter means that the device exerts a minimal flow restriction. In the unlikely event that filter regeneration failed, and the filter became blocked, an alternative route for the exhaust gas would always exist. The back pressure which is exerted on the engine can be pre-determined to always remain within OEM prescribed back pressure limits.

Controlled Filter Regeneration

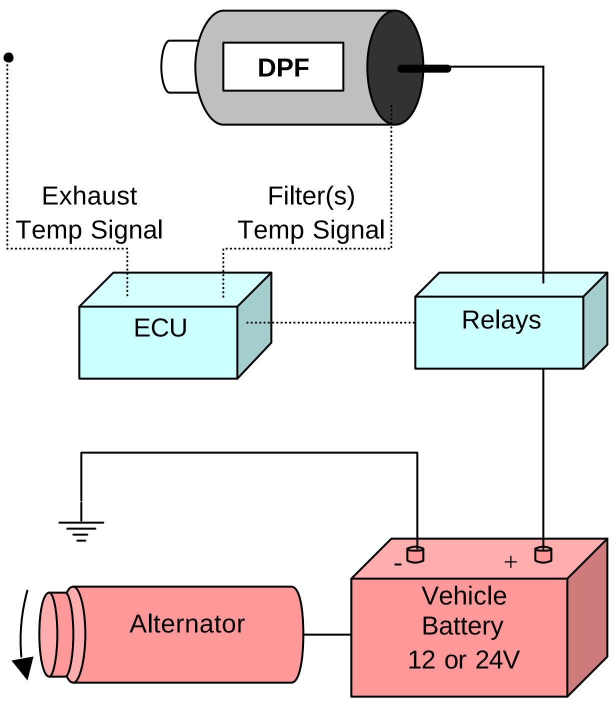

Figure 5 – Schematic Representation of Filter Control System

A method has been developed to regenerate the filter cartridge/cartridges automatically whilst the vehicle is in operation. The central component of this process is an electronic control unit (ECU) incorporating a microprocessor which constantly monitors the pre-device exhaust gas temperature and the filter temperature(s) using K-Type thermocouples. A correlation between the exhaust gas temperature and exhaust particulate concentration is used to determine the level of particulate deposition within the filter. As increased load is exerted on a diesel engine the exhaust gas temperature and the particulate level both increase.

Therefore, the controller uses exhaust temperature as an indicating parameter of how much particulate is being generated by the engine and entering the filter. The controller records the amount of time spent in a particular temperature band and the level of these bands are set depending on the maximum-recorded exhaust gas temperature. The controller regenerates the filter by triggering a relay based on the amount of time that the vehicle's exhaust temperature has spent in each band.

During regeneration the filter is heated until the temperature reaches approximately 550-600^{o}C when the power to the filter is switched off. At this point, an external power source is no longer required due to the exothermic nature of the particle oxidation reaction.

The CPU within the controller is fully programmable to allow the control algorithm to be tailored for installation of the system on any particular vehicle type.

Figure 6 - Electronic Control Unit for Filter Monitoring and Regeneration

Fuel Sulphur Tolerance

High fuel sulphur is known to cause problems with some of the available diesel aftertreatment technologies [5]. The power trap has been tested and proven to work with diesel fuel up to 2000 ppm.

Compliance with 2005 On-Board Diagnostics Requirements

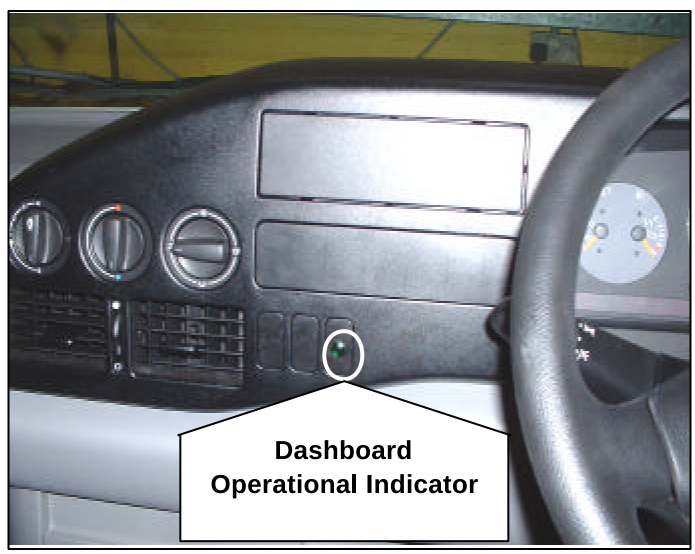

Figure 7 – 2005 OBD Requirements

The system has already been designed to include 2005 requirements of on-board diagnostics. Figure 6 shows an LED indicator on the dashboard of a Volkswagen LT35 light duty commercial van which has been fitted with the technology. The system control unit illuminates the LED if there is a device malfunction which leads to a reduction in the performance of the aftertreatment device.

Low Power Source Requirement

The system has a low power source requirement and is powered from the vehicle's own electrical system. This does not result in a performance penalty on vehicle operation. The electrostatic precipitation process (continuous DC) has an average power consumption of approximately 15 Watts on both 12 and 24V vehicle electrical systems.

On light duty vehicles with 12V electrical systems, the periodic filter regeneration process takes place every 12-15 hours and requires an average of 40 Amps for a 60-80 second period. On heavy duty diesel vehicles with 24V electrical systems, the filter regeneration process is required after every 4-7 hours of vehicle operation and consumes an average of 35 Amps.

High Ultrafine Removal

It has been proven that the smallest particles (which by number are the majority) have the most adverse effects on human health due to the fact that they can travel further into the sensitive regions of the lung [12, 13]. SMPS tests have been conducted with the PowerTrap fitted to a range of different vehicles and ultrafine PM reductions of up to 99% were achieved.

The lack of any feasible solution to the ultrafine problem has so far restricted the introduction of number-based PM regulations. The fact that the majority of particle mass and the majority of the particle number exist in different size ranges means that it is possible to achieve good mass-based results and therefore satisfy mass-based emissions regulations without having a significant effect on particle number.

Therefore, it can be argued that particulate emissions regulations need to be changed to focus on particulate number, not mass, if they are to have the desired health benefit. This is a view shared by Majewski [14], who states that because the majority of engine manufacturers are switching over to higher injection pressures and common rail technology, particulate mass is falling but particulate number is actually increasing.

Other system advantages include excellent noise reduction properties and the fact that the system has been designed as a flexible platform in order to accommodate a variety of different DPF technologies and coatings.

TEST RESULTS

This section details some of the SMPS test results that have been achieved with the PowerTrap fitted to a range of light and heavy duty vehicles.

Light Duty Tests

Figures 8-10 show tests performed to assess the ability of the technology to remove ultrafine particles [16]. The vehicle used in these tests was a Metrocab taxi powered by a 2.5l turbocharged Toyota diesel engine. Scanning Mobility Particulate Sizing (SMPS) scans were taken at steady state over the full range of vehicle operating conditions (idle, 15, 30, 50, 70, 100 and 120 km/h). Measurements were taken with the standard vehicle silencer and then with the device fitted. A total of three scans were carried out at each condition and from these, an average was taken. Figs 8-10 show the scan results from idle, 50 km/h and 120 km/h. As can be seen, there is a significant reduction in emitted particles over the whole size range when the device is fitted. Results of a similar nature were also achieved at each of the other steady state conditions and with two other taxis, an LTI (London Taxis International) powered by a 2.7l Nissan and a Metrocab powered with a 2.7l Ford engine (both naturally aspirated).

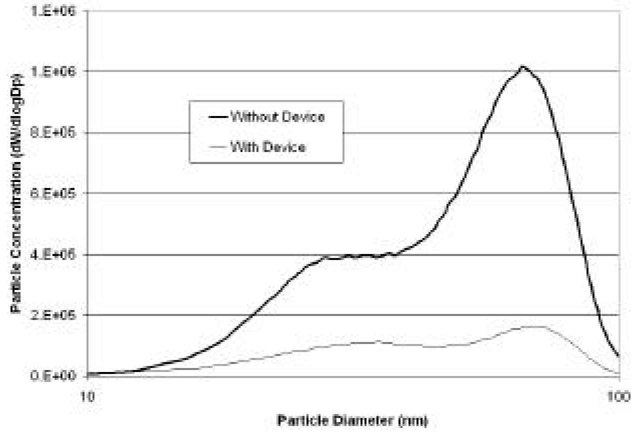

Fig 8 - Steady State SMPS at Idle – 2.5l Toyota Metrocab

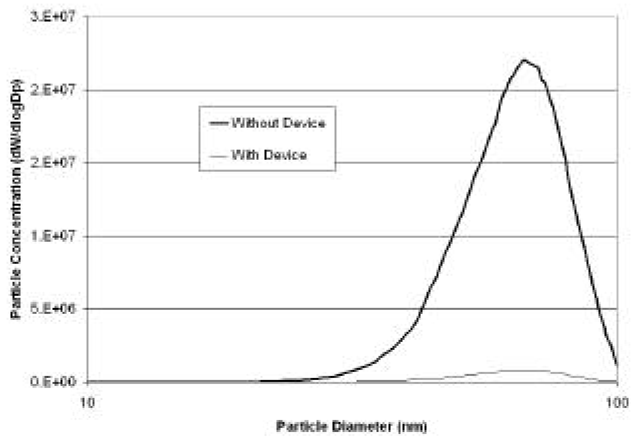

Fig 9 - Steady State SMPS at 50km/h – 2.5l Toyota Metrocab

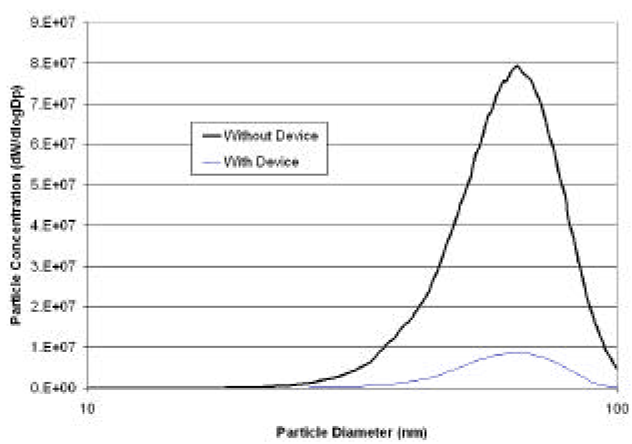

Fig 10 - Steady State SMPS at 120km/h – 2.5l Toyota Metrocab

A test was performed to assess removal of particles in this size range over transient conditions. Figure 12 shows the single size 60nm CPC particle count data for the Ford 2.7l Metrocab over the whole MVEG cycle, cold start with and without the device. The MVEG cycle is a standard urban drive cycle, which consists of 4 ECE cycles repeated back-to-back followed by one higher speed EUDC (extra urban drive cycle) to represent more aggressive driving conditions such as on a ring road or motorway. Fig 11 shows speed vs. time for the MVEG cycle.

High reductions were achieved in readily respirable 60nm particles over the entire transient cycle. The vehicle was cycled from cold start idling through light duty transients with low exhaust temperatures through to heavier duty transients. High reduction efficiencies (>90%) were achieved over the majority of the test cycle.

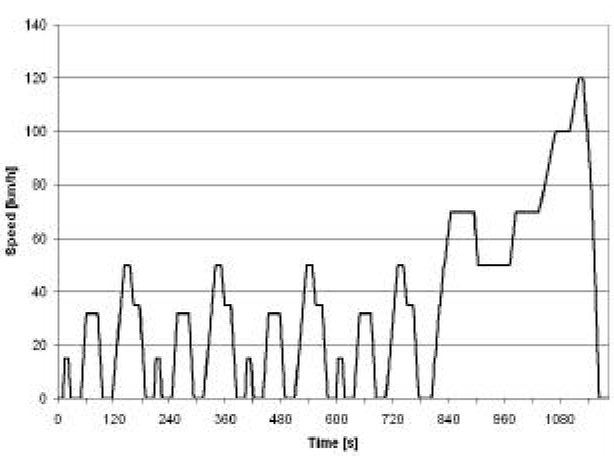

Fig 11 – MVEG Transient Drive Cycle

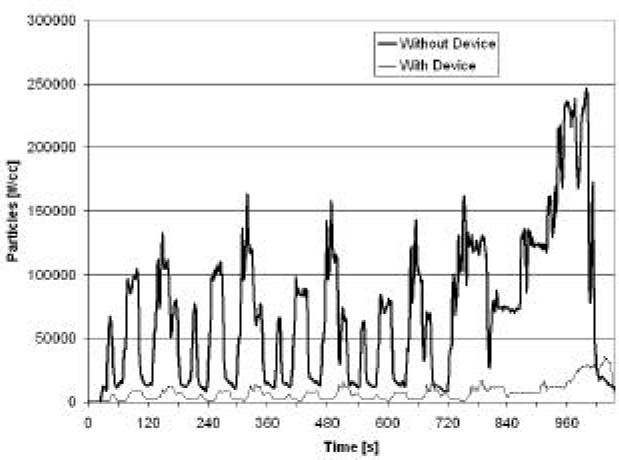

Fig 12 – 60nm CPC for 2.7l Metrocab over MVEG

Heavy Duty Tests

The device was tested on a range of fire appliances to assess the effectiveness of the technology on heavier duty engines over a range of operating conditions. A special RTA drive cycle was developed to accurately simulate on-road driving of a fire appliance using real data taken from a variety of different call-out situations. The drive cycle consisted of three phases: response journey to emergency call, water pumping at incident site and return journey to the fire station. Single size SMPS tests were carried out over the drive cycle and the 60nm particle reduction results are shown in Fig 14. The vehicle used in this test was a pre-Euro specification Scania Bronto. During the response and return phases of the cycle, the exhaust gas temperature varied between 300 and 400^{o}C. During the pumping phase of the cycle, the exhaust gas temperature dropped to approximately 110^{o}C. This gives a definite indication of the non-temperature dependence of this technology.

Average point-point reduction efficiencies for the three stages of the RTA test cycle are as follows:-

Phase	Average Point to Point Reduction %
Response	92.12
Pumping	97.77
Return	93.08

Table 1 – Reduction Efficiencies during RTA Cycle

Health risks from the diesel emissions from a fire appliance are high due to the high exposure limits in an 'on call' situation where operatives are working close to the appliance as it emits high levels of particulate during water pumping. Operation of the pump on a fire appliance requires a relatively high engine speed with the engine under moderate load. Figure 15 shows results from an SMPS scan (7 to 320nm) over the pumping phase which was simulated by recirculating water through high pressure hosing back into the main tank of the vehicle. Exhaust temperature stabilized at around 110^{o}C during the pumping cycle. Average point-point reduction over the scan range is 99.05 %.

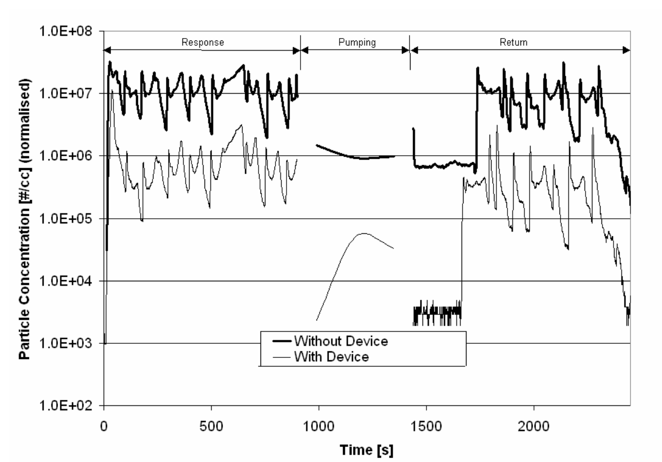

Fig 13 – Pre-Euro Fire Appliance CPC Data 60nm over RTA Cycle from Cold Engine Start

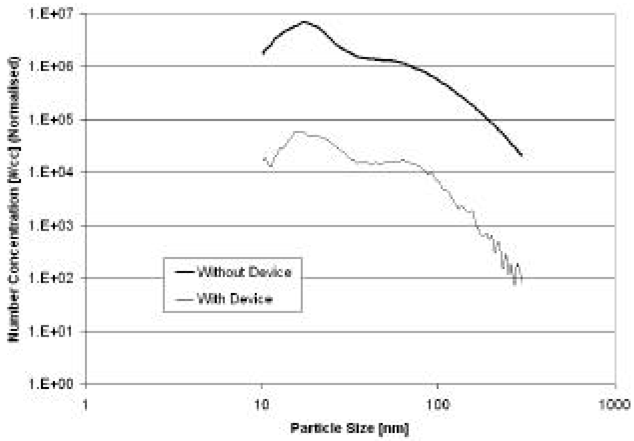

Fig 14 – SMPS Scan (7-320 nm) over Pumping Phase for Scania Bronto Pre-Euro Fire Appliance [18]

CASE STUDIES – VEHICLE INSTALLATIONS

The purpose of the following section is to show how this system has been successfully installed and integrated onto light and heavy duty vehicles: a VW LT35 van and a heavy duty fire appliance.

Case Study – VW LT35 Van

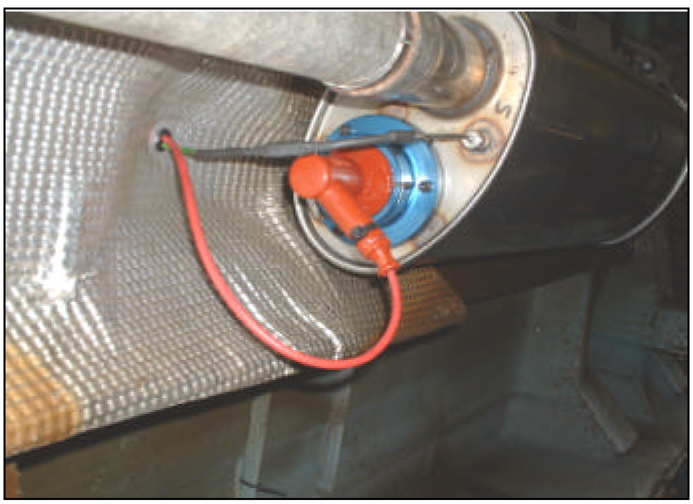

Figure 15 – Installation of Electrical Connections to PowerTrap on VW LT35 Van

Figures 15-17 show the device installed on a light duty VW commercial van. The system has been engineered to fit within the confines of the original exhaust silencer and therefore is a direct replacement. The non-temperature dependent nature of the technology means that it does not need to be installed close up to the exhaust manifold of the engine. Figure 15 shows the front end of the silencer and the high voltage connection which feeds the particle ionization electrode. The other smaller wire is from a K-type thermocouple which supplies an exhaust temperature signal to the system control unit. Figure 16 shows the whole silencer and Fig 17 shows the system control unit installed in a discrete position on the vehicle chassis.

Fig 16 - Installation of PowerTrap Silencer on VW LT35 Van

Figure 17 - Installation of System Control Unit on VW LT35 Van

Case Study – Heavy Duty Fire Appliance

Fig 18 – Fire Appliance Test Vehicle

The system has also been installed to an ex-fire brigade 8.5ltr Mercedes fire appliance which is currently used as a test vehicle in this research. Fig 19 shows the silencer and its electrical connections when installed on this vehicle.

Fig 19 – PowerTrap Installed on Fire Appliance Test Vehicle

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REFERENCES

1. Monaghan, M.L., "Particulates and the diesel – the scale of the problem", Diesel Engines – Particulate Control, IMechE Seminar Publication, 1998.
2. Health Effects Institute. 1995. Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects (A Special Report of the Institute's Diesel Working Group). Health Effects Institute, Cambridge, MA.
3. Donaldson K, Li X.Y., MacNee W, "Ultrafine nanometer particle mediated lung injury", J Aerosol Sci, 29 5, 1998.
4. Brear, F, "Diesel exhaust particle emissions: an engine manufacturer's contribution to the debate", The Science of the Total Environment, Vol. 235, 1999.
5. Carberry, B, Horrocks, R, Backes ,R and Ketcher, D, "A focus on current and future particulate after-treatment systems", Diesel Engines – Particulate Control, IMechE Seminar Publication, 1998.
6. Diesel Filter Regeneration, DieselNet Technology Guide, 2001.
7. DECSE, 2000a. "Phase I Interim Data Report No. 4: Diesel Particulate Filters", US DOE, 2000, http://www.ott.doe.gov/decse/pdfs/interim4.pdf
8. White, H.J., "Industrial Electrostatic Precipitation", Addison-Wesley, 1963.
9. Oglesby, S, "Electrostatic precipitation", New York : M. Dekker, 1978.
10. Wright, J, Kukla, P, Ball, A, Gu, F and Bann, J, "A Novel Electrostatic Method of Ultrafine PM Control Suitable for Low Exhaust Gas Temperature Applications", SAE Paper No 2003-01-0771.
11. Berry, E, 'Diesel Engine Pollutant Prediction and Remote Vehicle Monitoring, Part II: Remote Vehicle Smoke Emission Prediction-End-User Application', The International Journal of COMADEM, Submitted June 2003.
12. Kittelson, D.B., "Engines and Nanoparticles: A Review", J. Aerosol Science, Vol. 29, No 5/6, 1998.
13. Donaldson K, Li X.Y., MacNee W, "Ultrafine nanometer particle mediated lung injury", J Aerosol Sci, 29 5, 1998.
14. Majewski, W.A., "The nature of diesel Nanoparticles may require rethinking of particulate matter standards", Diesel Progress, June 1998.