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TITLE:

PARTICULATE EMISSION REDUCTION THROUGH ELECTROSTATIC TRAPPING AND DEEP BED FILTRATION

Topic:

- FUTURE AUTOMOTIVE TECHNOLOGY INTELLIGENT TRANSPORTATION SYSTEMS
 USER FRIENDLY AUTOMOBILE ADVANCED PRODUCTION AND LOGISTICS
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Abstract:

The environmental and health threats from sub-micron particulate matter emitted in significant amount from automotive vehicles have prompted investigation of techniques capable of efficiently trapping particulates from engine exhausts. Simple analytical studies have indicated that filtration and use of electrostatic fields are effective in controlling particle emissions. A laboratory particulate trap based on combined metallic mesh and fibrous filter and a wire-cylinder electrostatic trap have been investigated on a diesel engine. The traps under development to reduce emissions from vehicles showed promising initial results. In the next phase of experimental and modelling work, the particulate oxidation at typical exhaust temperatures, using electrical heating will be examined.

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INTRODUCTION

Following recognition of the adverse health effect that may be associated with breathing severely polluted air, concern for ambient air quality has long been reflected in legislation demanding the control of emissions to atmosphere. The single major source of urban pollution is from road transport which is powered by internal combustion engines. Emissions from road transport are growing steadily in line with increasing traffic. The growth in the number of vehicles and the distance traveled per vehicle mean that air quality in the critical areas such as many big cities remains bad and often gets even worse.

Particulate matter has been identified to be the major air pollution problems in urban environments in Thailand (1). Particle emissions from vehicles are currently under close scrutiny with respect to their contribution to atmospheric aerosol particles relative to other sources. It was estimated that within urban areas, the contribution of road transport to particulate matter exceeded 80 % (2). There is convincing epidemiological evidence that exposure to high ambient levels of these particles is associated with adverse health effects. The effects range from increased incidences of pneumonia and asthma, exacerbation of chronic obstructive pulmonary diseases, increased respiratory symptoms, and decreased lung function, to an increased mortality rate. Numerous studies in Europe and the USA (3, 4) have shown a strong correlation between mortality/morbidity from cardio-respiratory causes and exposure to PM₁₀, defined as particulate matter passing through a size selective inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter. Those at great risks are infants, children, elderly people and people with chronic respiratory diseases. Thailand's recent study of the relationship between PM₁₀ and daily mortality in Bangkok (5) found that a 10- $\mu\text{g}/\text{m}^3$ change in daily PM₁₀ is associated with a 1-2 % increase in natural death, a 1-2 % increase in cardiovascular mortality, and a 3-6 % increase in respiratory mortality. Fundamentally, the danger arises from the size spectrum. Small airborne particles can penetrate the human respiratory system deep into the smallest respiratory tracts and parts of the lungs during inhalation and a small fraction deposits on the surface of the airways. In this way, various and potentially hazardous organic and inorganic materials can be introduced into the human body, which may damage the lung tissue and cause cancer. The hazard caused by inhaled particles depends on their surface area and chemistry as well as on the site at which they deposit within the respiratory system.

Both diesel and gasoline vehicles contribute greatly to airborne particulate matter. On a mass basis, diesel engines have been regarded as the principal source of vehicle particulate emissions, however, gasoline particle mass emissions can be significant under high load and rich mixture conditions including cold starts and acceleration (6). On a number concentration basis, gasoline particles can be comparable with those of diesel vehicles. It is therefore essential that regulation and research effort should be directed towards both diesel and gasoline particulate emissions. It is very important to substantially reduce particulate emissions from automotive vehicles. Further improvements in engine design and operation might not be sufficient to meet the regulated standard, an after-treatment device will therefore be required. Efforts have been made in the field such as in (7-12). A possibility for the reduction of tailpipe

particulate emissions is the use of particle filter. Particle filters are open-pore wall-flow systems, designed either as foams or loosely sintered grains or as textile fiber structures. Pore sizes determine the pressure loss and are in the range of 10 to 100 μm . Trapping occurs due to impaction, interception and diffusion (13). There are many different types and they are normally classified depending on their filtering mechanisms, deep-bed and surface filters. Filter media used include fibrous mats, woven silica fiber, ceramic or metal foams, wire mesh, ceramic wool, sintered metal or ceramic monoliths. Filtering particulate matter entails a compromise between two conflicting demands, filtration efficiency and backpressure in the exhaust system. A good particle filtration system should therefore ameliorate this conflict.

The objective of the present research is to investigate techniques capable of efficiently trapping particulates from automotive engine exhausts. The programme involves mathematical modelling and experimental study of a simple particle trap based on a wire-cylinder electrostatic and a multi-candle filter configuration.

DEPOSITION MODELING

Analytical study of particle laden gas flow in an exhaust pipe was carried out (14), based on existing particle transport models in the literature including diffusive, thermophoretic gravitational and electrostatic effects. Representative engine conditions in exhaust pipe were simulated. It was found that the influence of diffusive, thermophoretic and gravitational forces was not sufficiently strong to produce satisfactorily high particle removal efficiency while electrical force may achieve particle capture efficiency up to and above 50 % under actual engine operation. Computational study of a relatively simple wire-cylinder trap was later undertaken (15). The CFD modeling of gas flow field was solved by a commercial software package, using a finite element method. Turbulent effect was calculated from the solution of the conservation equations of turbulent kinetic energy and turbulence dissipation rate in the k-e model. Trajectories of a large number of discrete single particles were tracked from their motions through the previously calculated gas flow field. The particle equation of motion included the effects of gravity, aerodynamic drag and electrostatic force. The electric field was specified by an analytical solution for corona electrodes for cylindrical pipe geometry. A wire electrode of 6.35 mm diameter was assumed with applied voltage up to 10 kV. Particles were charged by diffusion and field mechanisms. Particles in the range between 10 nm to 10 μm were used in the computation. It was found that, for a bundle of four parallel pipes of diameter 25 mm, 0.5 m in length at a voltage of 10 kV, trapped fraction of approximately 70 % could be achieved.

EXPERIMENTAL SYSTEM

Particulate Traps

There are two types of particulate trapping system considered here; (i) electrostatic trap, and (ii) deep bed filter. Figure 1 shows basic structure of the traps under development. For the deep bed filter, combination of two different filter media was considered, namely, metallic mesh and ceramic fibrous mats (47 % Al_2O_3 , 53 % SiO_2 , fibre diameter = 2.5 μm , bulk density = 160 kg/m^3). The material of metallic mesh is aluminium based. The whole filter consists of a bundle of four filter candles, housed in parallel inside a 0.22 m x 0.14 m, 0.55 m long round box, shown in Figure 1(a, b). The filter candle is

made of a 25 mm in diameter perforated tube of about 0.15 m long, wrapped along its length by a layer of metallic mesh on the inside, 20 mm thick ceramic fiber and metallic mesh on the outside. The grade of mesh was gradually finer from the candle filter entrance to exit, to achieve uniform trapping of particles inside the system. The gas flow direction would be radially inwards for each filter candle. Meanwhile, a simple electrode-cylinder electrostatic trap prototype was constructed, consisting of four grounded stainless steel pipes of 12.5 mm diameter and 0.5 m length in parallel with central discharge electrodes of 6.35 mm wire, shown in Figure 1(c). The electrode was energized by a high voltage power supply.

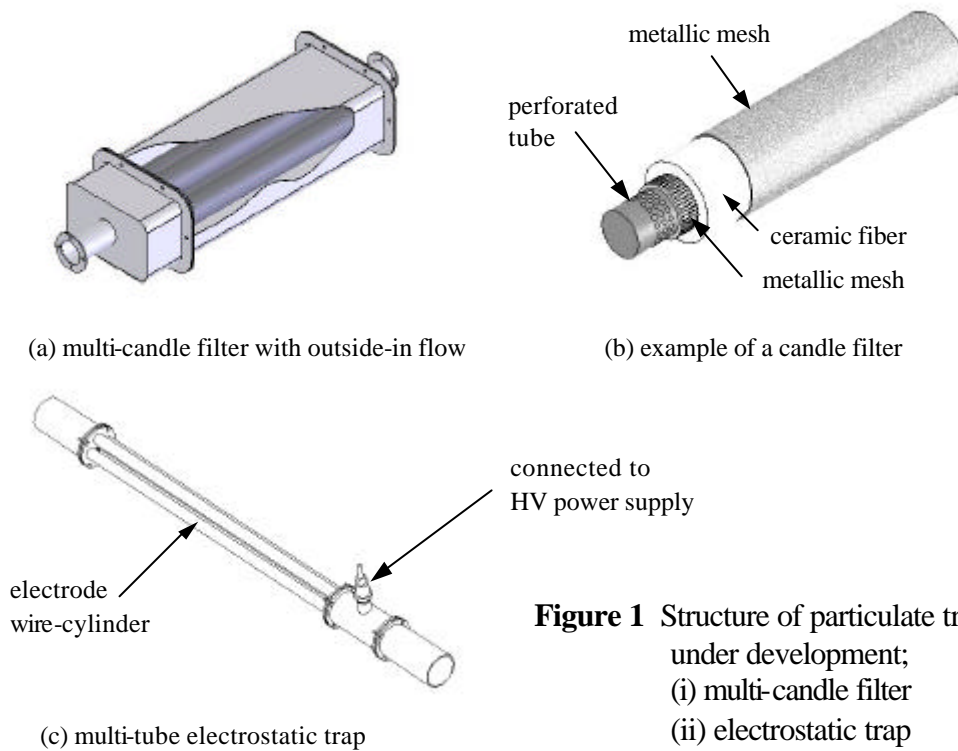


Figure 1 Structure of particulate traps under development;
(i) multi-candle filter
(ii) electrostatic trap

Engine Setup

The particulate traps were tested in a laboratory-scale engine test bed. The set-up of the experimental engine and apparatus is illustrated in Figure 2.

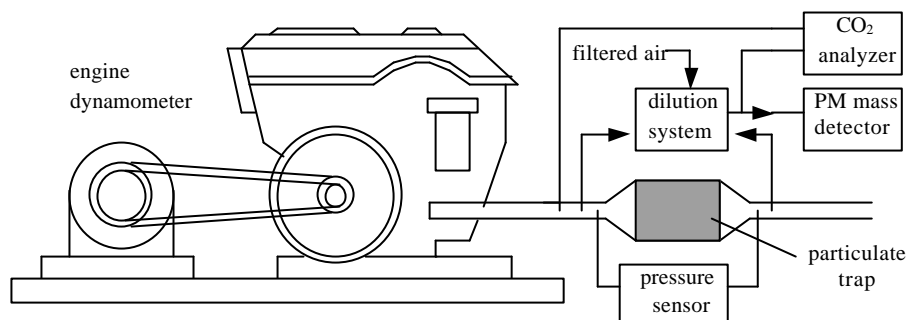


Figure 2 Experimental test rig for trap evaluation

Table 1 Test engine specifications

Engine	: Mitsubishi
Model	: Cyclone L200
Type	: 4-cylinder, 4-stroke, swirl chamber, diesel
Bore x Stroke	: 91 mm x 95 mm
Displacement	: 2477 cc
Nominal rated power	: 67 kW/4200 rpm
Maximum torque	: 167 Nm/2000 rpm
Compression ratio	: 21:1

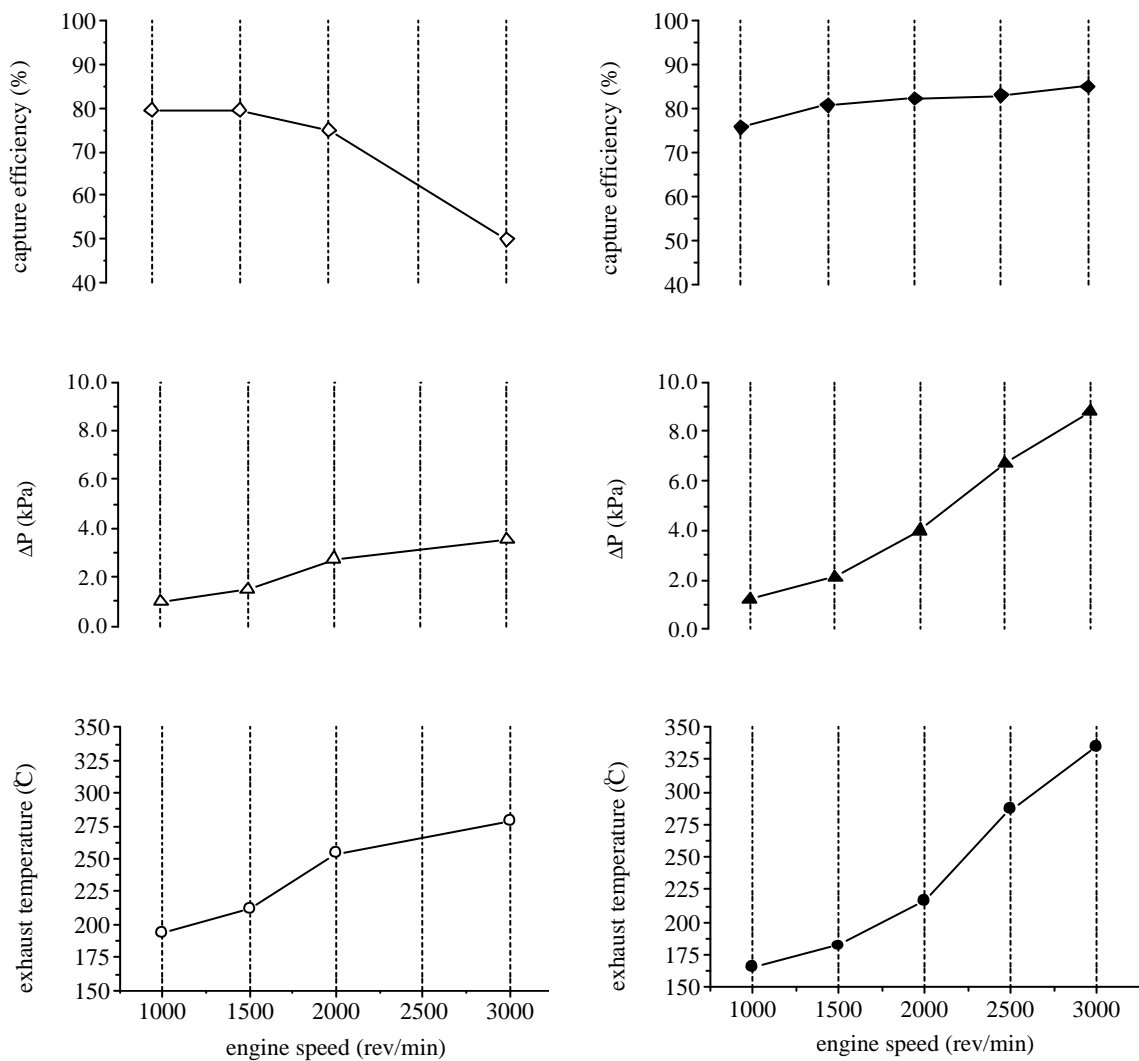
Diesel particulate matter was generated using a medium-sized diesel engine. Specifications of the test engine are shown in Table 1. The engine was coupled to a 75 kW dynamometer to allow for accurate manual speed and load control. A trap was fitted to a straight 50 mm exhaust pipe at a location about one third of the way between exhaust manifold and exhaust pipe exit. Testing was carried out by applying a fixed load and varying the engine speeds from 1000 to 3000 rpm. Each of these steady states was maintained for about 20 minutes following a 10 minute stabilization period and the data acquisition was then undertaken. The fuel used was commercial diesel. Engine speed was measured by a tachometer. The air mass flow rate was estimated using an air flow meter. Digital type k thermocouples, connected to a data logger, were installed to measure all the relevant temperatures.

Particulate matter was sampled using a 5 mm stainless steel probes and diluted with filtered air in a two-stage ejector system, similar to that used in Tippayawong 's work (16). Measurements of particle mass concentration were made using an optical particle mass detector in which it had previously been calibrated with a weighted filter experiment. Particulate mass concentrations from both methods agreed reasonably well. Particulate trapping efficiency is calculated from the ratio of the difference between upstream and downstream particulate mass concentrations to upstream particulate mass concentration. Pressure drops across the trap were measured by a differential pressure sensor. Several readings were repeatedly taken and the average value was computed.

TRAP PERFORMANCE

Experiments have been performed for the two traps developed with diesel particles at exhaust gas mass flow rates up to 0.05 kg/s, giving residence times in the traps of the order of 50-500 ms. Figure 3(i) depicts trapping efficiency, pressure drop and exhaust gas temperature for a range of engine speeds. Without the electric field ($V = 0$ kV), there would be negligible change in particle concentration. With applied voltage ($V = 10$ kV), large fraction of particulate matter was expected to deposit inside the trap. From the results obtained, particle mass concentrations at outlet were found to be smaller than at the inlet, giving rise to trapping efficiency around 50-80 % depending on engine speeds. This was in similar magnitude as predicted by modeling work. Pressure drop across the electrostatic trap was observed to be small, being under 4 kPa for all exhaust gas flow rates tested. The electrostatic trap prototype appeared to work satisfactorily well from low to high engine speeds. Higher applied voltages as well as many more tube arrangements are likely to result in a better performance.

With respect to the multi-candle filter performance, particle capture efficiency as a function of engine speed is shown in Figure 3(ii), along with pressure drop and exhaust temperature. Increasing engine speed, resulting in higher gas flow rate, did not appear to affect capture efficiency of the multi-candle filter. In fact, it increased from about 75% at 1000 rev/min to about 85% at 3000 rev/min. However, pressure drop increases rapidly as exhaust gas flow rate increases. High filtration efficiency appeared to be accompanied by high pressure drop. This behaviour may result from the fact that particles accumulated and built up chains of deposited mass that acts as a collector itself, filtering particles from the exhaust gas stream. These particles end up to the previously deposited particle, building up more chains and obstructing flows. This time-dependent behaviour of pressure drop is shown in the next figure.



(i) electrostatic trap

(ii) deep bed filter

Figure 3 Measurements of prototype traps performance in experimental test rig
open symbols: for electrostatic trap. solid symbols: for deep bed filter

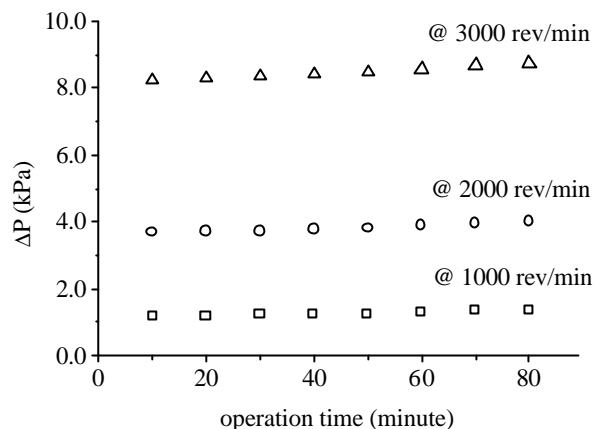


Figure 4 Pressure drop increase across a multi-candle filter with time during runs performed at different engine speeds

One of the most interesting parameter concerning trap operation is the progress of the induced backpressure or pressure drop across the trap. Figure 4 illustrates the pressure drop increase owing to particulate accumulation in the multi-candle filter, comparing cases with different engine speeds. These results were derived from only the data measured during the first 80 minutes of operation. The increase in pressure drop was marginal. Even though the rate of increase in backpressure was small, at longer period, it is expected to become excessive due to a progressive plugging of trapped particulate matter. High pressure drop increases fuel consumption and deteriorate vehicle's drivability.

CONCLUDING REMARKS

In order to achieve effective removal of particulate matter from tailpipe emissions, particulate traps have been in focus for a number of years. In this work, the particulate trap concept for particulate control, based on combined metallic mesh and ceramic fibrous filter and a wire-cylinder electrostatic precipitator, has been experimentally investigated on a diesel engine. It was found that the traps can achieve particulate trapping efficiency of 50-85% by mass, hence have the possibility to be applied as automotive particulate filter system.

The traps under development showed promising initial results, though a suitable and efficient regeneration method has to be found and tested in order to remove the trapped particulate preventing its build-up. Work is in progress to investigate the particulate oxidation at typical exhaust temperatures, using electrical heating and catalytic methods.

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