start of the regeneration process, there is a reduction in the soot content which in turn lowers the conversion of microwaves into heat, but this is more than compensated by the heat of combustion of the soot, thus there is a net gain in energy and spreading into the other part of the filter. There are regions inside the trap where the abovementioned conditions may not exist (e.g. on the far side of the microwave irradiation port, the entrance of the filter where the engine exhaust carries away the heat) regeneration become difficult.

In Figure 4.10 are some photographs of the cut-away views of regenerated filters showing the distribution of unburned soot. The burning of soot in the traps is a fan-shaped pattern, and there are considerably more soot at the inlet of the filter and on the far side to the microwave irradiation port left.

The main problem with uneven regeneration is the localization of the heat causing sintering of the substrate. Figure 4.11 shows the sintering of the filter wall at the source of the microwave irradiation. It is also possible to have sintering inside the filter leaving the walls untouched.

The microwave-assisted heating system was designed based on the wavelength of the microwaves, the physical (e.g., the fixed diameter of the filter, 144 mm) and dielectric properties of the filter, soot and catalyst. Since the operation of a diesel engine is dependent on many factors such as fuel, speed, load, temperature, and pressure, thus the soot produced would also be different; it is difficult to have a design which can handle all the soot produced at the optimal conditions. There are suggestions in the literature [20, 21] to more evenly distribute the microwaves in filters.

4.4 Conclusions

The Corning cordierite filters were found to be very effective in the filtration of soot generated from our diesel engine test bed, however, significant back pressure build up was experienced as the filtration proceeded, and at 0.0041 MPa, the performance of the engine deteriorated rapidly, thus regeneration of the soot trap was necessary. For the optimal operation of this technology in the abatement of soot emission from diesel vehicles, a combination of factors must be considered, this includes the filtration efficiency, the fuel consumption rate, the back pressure build up, and the regeneration cycle such that the vehicle can be operated close to normal conditions while satisfying emission regulations.

Two burning stages were observed in our engine test bed studies: the burning of the more easily combustible soluble organic fraction at the early stage (lower temperature) of the regeneration cycle, and the combustion of the solid carbonaceous matters when the temperature in the filter was higher. The presence of the catalyst in the filter significantly promoted combustion by lowering the ignition temperature as exemplified by the earlier (1 minute) combustion of the SOF and 5 minutes for the soot. This suggests that the catalyst enhanced the absorption of microwaves, promoted heating in addition to the lowering of the ignition temperature of the SOF and soot, thus saving energy and reducing thermal shocks.
to the ceramic substrate. Comparing the CO and CO$_2$ concentrations in the filter exhaust, it could be seen that the catalyst enhanced the burning rate, and higher CO$_2$/CO ratios indicated that more complete combustion took place thus reducing the amount of the secondary pollutant CO. The selection of a proper catalyst also prolongs the life of the filter.

The amount of soot to be regenerated is the key factor in the regeneration process. At a power level of 800 W, it took 28 minutes to regenerate a filter with a soot loading of 5.9 g l$^{-1}$ in the presence of Cu-V, while increasing the loading to 8.4 g l$^{-1}$ the regeneration time was reduced to 17 minutes; further increasing the loading to 11.0 g l$^{-1}$, only 9 minutes were required to regenerate the filter, however sintering occurred due to the intense burning.

It was difficult to completely burn off all the soot in the filter in the engine testbed studies: there were remnants in the entrance of the filter and at the far side from the entrance of the microwave port. The regenerated region exhibited a fan-shaped pattern originating from the entrance of the irradiation. The uneven distribution of the microwaves in the filter, the uneven deposition of the soot in the filter due to flow and geometry, and possibly the unevenness in the deposition of catalysts on the substrate, all could cause the incomplete regeneration of the filter.
References


(15) Tatsuki, I., Masatoshi, S., Tetsuya, O., Keiichi, T., and Masashi, S., "Development of diesel particulate trap systems for city buses", SAE 910138, 1991


(20) Metaxas, A.C. and Meredith, R.J., "Industrial Microwave Heating", IEE Power Engineering Series 4, Peter Peregrinus Ltd, 1983

<table>
<thead>
<tr>
<th><strong>Engine model</strong></th>
<th>4D68 Mitsubishi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total displacement, cm³ (cu. in.)</strong></td>
<td>1,998 (121.9)</td>
</tr>
<tr>
<td><strong>Cylinder bore/stroke, mm (in.)</strong></td>
<td>82.7/93 (3.256/3.661)</td>
</tr>
<tr>
<td><strong>Compression ratio</strong></td>
<td>22.4</td>
</tr>
<tr>
<td><strong>Valve mechanism</strong></td>
<td>SOHC (Single overhead cam)</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>Diesel oil</td>
</tr>
<tr>
<td><em><em>Maximum output, kW (horsepower</em>) / rpm</em>*</td>
<td>50 (68) / 4,500</td>
</tr>
<tr>
<td><strong>Fuel system</strong></td>
<td>Distribution type injection pump</td>
</tr>
</tbody>
</table>

*1kW = 1.34 hp

Table 4.1 Diesel engine specifications
<table>
<thead>
<tr>
<th>Time min</th>
<th>Pressure, MPa</th>
<th>Temperature, C</th>
<th>Soot content, Rb</th>
<th>Acc. soot, g</th>
<th>Soot Removal %</th>
<th>Gas concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>delta P</td>
<td>T2</td>
<td>T3</td>
<td>SO₂ ppm</td>
</tr>
<tr>
<td>0</td>
<td>0.0007</td>
<td>0.0000</td>
<td>0.0007</td>
<td>188.5</td>
<td>125.9</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.0014</td>
<td>0.0000</td>
<td>0.0014</td>
<td>207.0</td>
<td>166.4</td>
<td>7.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0026</td>
<td>0.0003</td>
<td>0.0023</td>
<td>214.3</td>
<td>174.4</td>
<td>11.6</td>
</tr>
<tr>
<td>10</td>
<td>0.0026</td>
<td>0.0003</td>
<td>0.0023</td>
<td>218.5</td>
<td>182.5</td>
<td>11.6</td>
</tr>
<tr>
<td>20</td>
<td>0.0028</td>
<td>0.0003</td>
<td>0.0024</td>
<td>226.7</td>
<td>191.8</td>
<td>12.1</td>
</tr>
<tr>
<td>30</td>
<td>0.0031</td>
<td>0.0003</td>
<td>0.0028</td>
<td>230.5</td>
<td>197.5</td>
<td>14.1</td>
</tr>
<tr>
<td>45</td>
<td>0.0034</td>
<td>0.0003</td>
<td>0.0031</td>
<td>232.4</td>
<td>199.0</td>
<td>15.6</td>
</tr>
<tr>
<td>56</td>
<td>0.0037</td>
<td>0.0003</td>
<td>0.0034</td>
<td>236.1</td>
<td>201.7</td>
<td>17.1</td>
</tr>
<tr>
<td>67</td>
<td>0.0041</td>
<td>0.0003</td>
<td>0.0038</td>
<td>239.0</td>
<td>203.1</td>
<td>19.1</td>
</tr>
<tr>
<td>80</td>
<td>0.0044</td>
<td>0.0003</td>
<td>0.0041</td>
<td>242.4</td>
<td>205.9</td>
<td>20.6</td>
</tr>
<tr>
<td>100</td>
<td>0.0047</td>
<td>0.0003</td>
<td>0.0043</td>
<td>248.8</td>
<td>209.5</td>
<td>21.6</td>
</tr>
</tbody>
</table>

Note: P1 = filter inlet pressure or back pressure (BP). P2 = filter outlet pressure. Delta P = pressure drop across the filter. T2 = filter inlet temperature. T3 = filter outlet temperature. Rb = Bosch smoke scale. S1 = soot content in inlet stream, Rb. S2 = soot content in outlet stream. Soot removal % = (S1 - S2)/S1 * 100. Acc. = soot accumulated in the filter. Based on the total mass of soot trapped at the end of filtration (21.6 g) which corresponded to a back pressure of 0.0043 MPa, and assuming a linear relationship between the soot mass and the back pressure.

Table 4.2 Transient properties of the filtration process
<table>
<thead>
<tr>
<th>RPM</th>
<th>Load, N-m</th>
<th>Power, kW</th>
<th>Exhaust temp., °C</th>
<th>$O_2$, %</th>
<th>Soot, Rb</th>
<th>TG-DSC, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>950</td>
<td>0</td>
<td>0</td>
<td>95.7</td>
<td>16.3</td>
<td>0.9</td>
<td>510.2/590.7²</td>
</tr>
<tr>
<td>1450</td>
<td>70</td>
<td>20</td>
<td>184.5</td>
<td>14.4</td>
<td>1.0</td>
<td>574.5</td>
</tr>
<tr>
<td>1450</td>
<td>125</td>
<td>35</td>
<td>304.1</td>
<td>10.9</td>
<td>3.4</td>
<td>620.9</td>
</tr>
<tr>
<td>1450</td>
<td>190</td>
<td>53</td>
<td>385.0</td>
<td>8.3</td>
<td>5.7</td>
<td>648.3</td>
</tr>
<tr>
<td>2000</td>
<td>70</td>
<td>27</td>
<td>313.0</td>
<td>10.1</td>
<td>1.9</td>
<td>597.0</td>
</tr>
<tr>
<td>2000</td>
<td>125</td>
<td>48</td>
<td>430.0</td>
<td>7.9</td>
<td>4.1</td>
<td>635.8</td>
</tr>
<tr>
<td>2400</td>
<td>70</td>
<td>32</td>
<td>330.0</td>
<td>10.6</td>
<td>1.4</td>
<td>605.0</td>
</tr>
</tbody>
</table>

1 Conditions: 10% $O_2$ in $N_2$, 10 °C min⁻¹ temperature rise. Sample size: 4-5 mg. The temperature is the temperature at the maximum mass loss.

2 Two weight loss peaks were observed.

Table 4.3 Burning characteristics of soot produced and oxygen concentration in the exhaust at various engine conditions

<table>
<thead>
<tr>
<th>Filter sample</th>
<th>R</th>
<th>B</th>
<th>C</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soot loading, g l¹</td>
<td>8.1</td>
<td>8.2</td>
<td>8.4</td>
<td>8.3</td>
</tr>
<tr>
<td>Regeneration time, min.</td>
<td>25</td>
<td>20</td>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.4 Regeneration time

<table>
<thead>
<tr>
<th>Sample</th>
<th>Soot loading, g l¹</th>
<th>Regeneration time, min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>5.7</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>&gt;40</td>
<td>24</td>
</tr>
<tr>
<td>C</td>
<td>5.9</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>19</td>
</tr>
</tbody>
</table>

* Slight sintering of a part of the filter wall.

** Several holes on the filter wall were produced due to melting; temperature exceeded 400 °C.

Table 4.5 Regeneration time of Samples R and C at different soot loadings
<table>
<thead>
<tr>
<th>Time, min.</th>
<th>0</th>
<th>1</th>
<th>3</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
<th>5.5</th>
<th>6.5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>18</th>
<th>20</th>
<th>22</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC, ppm</td>
<td>70</td>
<td>80</td>
<td>70</td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>80</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>110</td>
<td>110</td>
<td>150</td>
<td>250</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>CO, ppm</td>
<td>270</td>
<td>290</td>
<td>320</td>
<td>740</td>
<td>1080</td>
<td>1280</td>
<td>1440</td>
<td>1530</td>
<td>1380</td>
<td>1430</td>
<td>1540</td>
<td>1840</td>
<td>2280</td>
<td>2640</td>
<td>3620</td>
<td>1440</td>
<td>940</td>
<td>320</td>
</tr>
<tr>
<td>O₂, %</td>
<td>14.1</td>
<td>13.85</td>
<td>13.7</td>
<td>13.6</td>
<td>13.5</td>
<td>13.3</td>
<td>13</td>
<td>12.9</td>
<td>13.07</td>
<td>13.5</td>
<td>13.1</td>
<td>12.72</td>
<td>12.4</td>
<td>12.2</td>
<td>11.9</td>
<td>13.2</td>
<td>13.4</td>
<td>13.8</td>
</tr>
<tr>
<td>CO₂, %</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.7</td>
<td>3.9</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3.9</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4.1</td>
<td>4.3</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Inlet temperature of filter, T2 = 102 °C

Table 4.6 Concentration variations in HC, CO, O₂ and CO₂ during Sample R regeneration

<table>
<thead>
<tr>
<th>Time, min.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC, ppm</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>70</td>
<td>80</td>
<td>110</td>
<td>110</td>
<td>120</td>
<td>140</td>
<td>150</td>
<td>250</td>
<td>310</td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>CO, ppm</td>
<td>330</td>
<td>370</td>
<td>780</td>
<td>1360</td>
<td>1750</td>
<td>1210</td>
<td>1250</td>
<td>1370</td>
<td>1840</td>
<td>2280</td>
<td>2740</td>
<td>4680</td>
<td>1950</td>
<td>640</td>
<td>360</td>
</tr>
<tr>
<td>O₂, %</td>
<td>13.8</td>
<td>13.5</td>
<td>13.1</td>
<td>12.8</td>
<td>12</td>
<td>13.2</td>
<td>13.5</td>
<td>13.1</td>
<td>12.5</td>
<td>12.1</td>
<td>11.4</td>
<td>10.5</td>
<td>12.4</td>
<td>13.46</td>
<td>13.61</td>
</tr>
<tr>
<td>CO₂, %</td>
<td>3.5</td>
<td>3.5</td>
<td>3.7</td>
<td>4</td>
<td>4.5</td>
<td>4.2</td>
<td>4.1</td>
<td>3.9</td>
<td>4</td>
<td>4.1</td>
<td>4.6</td>
<td>6.54</td>
<td>4.8</td>
<td>3.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Inlet temperature of filter, T2 = 95 °C

Table 4.7 Concentration variations in HC, CO, O₂ and CO₂ during Sample C regeneration
Figure 4.2 Engine testbed sampling locations

Figure 4.3 Microwave generator

- T: Temperature sensor
- P: Pressure sensor
Figure 4.4 Photograph of filter housing, microwave control panel
Figure 4.5 Schematic of exhaust gas and soot analyzers.
Figure 4.6 Transient properties of the exhaust during filtration
Figure 4.7 Soot removal efficiency
Figure 4.8a Effect of filter back pressure on product distribution, CO, CO₂
Figure 4.8b  Effect of filter back pressure on product distribution, SO$_2$, NO, HC
Figure 4.9a  Exhaust composition during regeneration -- Samples R and C
Figure 4.9b Hydrocarbons produced during regeneration -- Samples R and C
Figure 4.10 Uneven regeneration of ceramic filter
Figure 4.11 Sintered ceramic filter
Chapter 5 Diesel soot abatement using emulsified fuel

Abstract

Diesel fuel emulsified with up to 15% by weight of water was studied in an engine testbed, and road tests were also conducted to determine its ability in reducing the emission of soot and other harmful air pollutants in the exhaust. A reduction of approximately 10 - 68% on testbed, and 36% in road tests in soot emission was achieved due to the more complete combustion induced by the "secondary atomization" by the water in the engine. The range of fuel savings was 1.0 to 6.0% while the average increase in fuel efficiency for the conditions studied was 2.9%. The average savings was 8% in the road tests.

From the engine testbed study, it was found that the emulsified fuel had a large impact on the composition of the exhaust gas. Less soot and nitrogen oxides were produced, however, there was an increase in carbon monoxide possibly due to the reaction between the carbon in the soot and the water in the exhaust, which was plentiful. In the study of the physical and thermal properties of the soot formed using emulsified fuels, it was found that the soot was more easily oxidized due to lower ignition temperatures, thus the residue soot could be more easily removed by a cleanup process where regeneration is needed.

The addition of water in the fuel, which was substantially more than what is normally in an engine, did not seem to cause extra wear and corrosion of the pistons and cylinders.

Keywords: emulsified fuel, diesel particles, fuel economy, engine corrosion

5.1 Introduction

Diesel engines are extensively used in the world for economical and practical reasons even though they emit more particulate matters than gasoline-powered engines. The carbon particulates, also known as "diesel soot or black smoke", emitted are the result of incomplete combustion of the diesel fuel in the engine cylinders. Tail-gas emissions are known to be one of the most serious environmental pollution problems and sources in urban areas. Hong Kong has one of the largest diesel fleet density in the world, as of 1995, 32% of the vehicle on the road is powered by diesel engine and most of them are the more frequently used transportation vehicles such as taxis, buses and trucks [1]. According to the 1989 Government White Paper on pollution in Hong Kong, 44% of all respirable particulates emitted in the territory came from diesel powered vehicles. It also made the strong statement that "Diesel emissions must therefore be a prime target for control". In a detailed 4-year study of the solvent-extractable organic compounds in the aerosols collected at 8 sites in Hong Kong, representing background, rural, urban, and street-level
conditions, the contribution from vehicular emissions was found to be 27 - 65% [2] on an annual basis. PAH, polycyclic aromatic hydrocarbons, known carcinogens were found in all samples and in quantities which may be significant to have health implications. The development of an effective diesel exhaust abatement system or technology suitable for local use is needed and can greatly improve our air quality.

The particulate matters or soot emitted from diesel engines contain mainly of unburned hydrocarbons, a large variety of combustion products, metals, and soot, carbonaceous material. The soot contains adsorbed heavier hydrocarbon compounds originated from diesel fuel and lubricating oil known as soluble/volatile organic fraction, SOF/VOF. There are also polycyclic aromatic hydrocarbons, PAH associated with these particles; all PAH and their derivatives are known to be carcinogenic [3-6]. These particles are very light, bulk density <0.08 g cm⁻³ and small, diameter <10⁻⁶ m [7], thus can travel a long distance, and could have a detrimental effect on human health and the environment.

Emulsifying a fuel with an additive, such as water, to enhance combustion has been researched for decades. Because of the promotion of more complete combustion, there is also an improvement in fuel economy. It is known to the petroleum refining industry that a smoky flare can be easily arrested by simply injecting steam into the stack. Some garage mechanics also claim engines run smoother during rainy days. There have been research carried out to study the effects of ejecting water into boilers to improve fuel efficiency [8-15], eventhough the phenomenon is not well understood. Other additives such as alcohols have also been considered. When using fuel additives as a means to reduce pollutants in a combustion system, it is important to note that the additives must not produce any secondary pollution.

When a water-emulsified diesel fuel is injected into the cylinder, the water droplets, finely distributed in the fuel phase, are heated. vaporize and they expand until micro-explosion takes place [12]; the water vapor bursts through the outer layer consisting of the fuel, experiencing what is known as a "secondary atomization". This further disperses the fuel in the combustion stream, generating turbulence to well-mix the contents in the cylinder. This mixing and dispersion of the fuel promotes a more complete and much cleaner burning. The end results are less soot and unburned hydrocarbons are formed, and because of the presence of water to cool down the burning, therefore less nitrogen oxides is produced. The fuel enveloped water droplets are <2 μm in diameter.

In general, there are two approaches taken in the study of emulsified diesel fuel on combustion: (1) to concentrate on the influence of the fuel on the performance of the engine and the emissions under realistic conditions [8-10], and (2) to study the mechanism of the burning of the two-phase droplets in a high temperature field [11-12]. The latter is not included in the present study.
In the present work, a ZSR emulsifier, Kentex Corporation, U.S.A. was used to emulsify the diesel fuel in a form suitable for direct combustion in diesel engines with or without stabilizing additives. This report describes the performance results produced on an engine testbed equipped with a Mitsubishi, 4D68 diesel engine and obtained from actual road tests derived from a 1985 Isuzu Aska 2.0L sedan using emulsified diesel fuels. The impact of using emulsified diesel fuels on fuel consumption, engine wear and exhaust composition, especially soot emission is presented.

5.2 Experimental

5.2.1 Diesel engine testbed

The diesel engine testbed used in this experiment contained four components: a 4D68 Mitsubishi 4-cylinder 4-stroke diesel engine with a displacement of 1998 cm\(^3\), a TS-135 Mustang dynamometer, a set of on-line exhaust analyzers, and a computer control system. The dynamometer could absorb a maximum of 370 kW of energy and the maximum engine speed was 5000 rpm, revolutions per minute. The computer was a PC-based desktop system with an Intel 286 processor. It used two models to control the speed and load of the engine to simulate the driving conditions by way of the dynamometer. Appropriate interfaces were used to link the computer to the engine and the dynamometer. The engine testbed is physically located in the Engine Laboratory of the Department of Mechanical Engineering. The procurement of the testbed was a joint venture between the Department of Mechanical Engineering and the Research Center. The specifications of the engine are listed in Table 5.1.

5.2.2 Fuel emulsification system

A schematic diagram of the diesel fuel emulsifier system is shown in Figure 5.1. The emulsifier was purchased from Kentex Corporation, U.S.A., Model ZSR. The system was designed such that up to 15% of water by weight can be emulsified into the fuel and the resulting mixture can be directly pumped into the diesel engine testbed. This circumvented the problem of phase separation due to gravity when left standing for a period of time. When the fuel was emulsified for road tests, a stabilizing additive was added such that the mixture could remain emulsified for 2 weeks. The system also allowed the delivery of only diesel fuel to the engine. The emulsified mixture was water in the dispersed phase.

Diesel fuel and water in the correct proportions were drawn at constant rates from storage tanks to the emulsifier by a pump, this is a part of the emulsifier and appropriate valvings. The pump was a part of the emulsifier. Valves V2, V3, and V8 were used for the selection of fuels, e.g., regular diesel fuel could be selected by closing V8. The water content was controlled by V1 and V4, and the flow rate was displayed by flow meter F1. V6, V7 and V9 were used to regulated the emulsifying time and the extent of emulsification by regulating the emulsifier inlet pressure, P1 to 210 - 250 psi, pound force per square inch, and the outlet pressure, P2 to 50 - 70 psi; P3 displayed the emulsion discharge
pressure, 5 - 25 psi. Closing V8 and opening V7, the emulsified fuel could be recycled back to the pump to either provide longer emulsifying time or to put the emulsifier in stand-by mode.

5.2.3 Exhaust gas and soot analyzers

The composition of the exhaust gas was analyzed using a set of Siemens on-line tailgas analyzers. Carbon monoxide (Ultramat 21P, 0-10%), carbon dioxide (Ultramat 21P, 0-18%), sulfur dioxide (Ultramat 13M, 0-1000 ppm), and nitrogen oxides (Ultramat 13M, 0-1000 ppm) were monitored continuously and data were reported at a rate of once per minute. Two Bosch smoke meters were used to measure the soot emitted and they were FQD-102A (Wenzhou Instrument Factory, China) and Hartridge MK-3 Smokemeter, 1-100 (Leslie Hartridge Ltd., England).

The thermal properties and characteristics of the diesel soot produced were analyzed using the following techniques: Thermogravimetry - Differential Scanning Calorimetry, TG/DSC (STA-409A, Netzsch, Germany - Mass Spectrometric), coupled with mass spectrometry (MS) for exhaust stream gas analysis (MS250, Extrel, U.S.A.), BET (ASAP 2000, Micromeritics, U.S.A.) for specific surface area determination, and Scanning Electron Microscopy - Energy Dispersion X-ray Spectrometer, SEM/EDAX (XL-30, Philips, Holland) for surface imaging and elemental measurements.

5.3 Engine testbed operation

The emulsifier was first turned on until a consistent emulsified fuel-water mixture at the desired composition was obtained. The system was placed on hold by recycling the fuel mixture until the diesel engine was ready to run on emulsified fuel.

The operation of the diesel engine testbed followed the SOP, standard operating procedure established by the Research Center and the Department of Mechanical Engineering. A copy of the SOP is attached in Appendix II. It took about 15 minutes for the testbed to warm up and reach a steady-state.

To conduct an experiment using diesel fuel, shut off V2 and V8, open V3 in the emulsifier system as shown in Figure 5.1. To use emulsified fuel, shut off V3 and open V8, after a steady stream of emulsified fuel has been previously prepared. V7 can be used to adjust the emulsified delivery rate by controlling the recycle stream. Adjust the load of the dynanometer and engine speed through the computer.

5.4 Results and discussion

A total of 300 hours of testing was conducted on the testbed to study the effect of water-emulsified diesel fuels on emissions, fuel economy, characteristics of the soot formed, and engine wear. This is equivalent to approximately 15,000 km traveled, roughly 1 year of mileage driven by an average U.S. commuter.

The engine speed was held in the range of 950 - 2400 rpm and the load was set at 0 - 256 N-m. The power produced was 0 - 40 kW. This is equivalent to normal driving on
relatively flat terrain. Excessive vibration of the testbed at engine speeds higher than 2400 rpm prevented operation at peak conditions.

The fuels used were regular diesel as purchased from a gas station near the University, and the deionized water in the fuel was 5, 10 and 15% by weight.

5.4.1 Impact of emulsified fuels on emissions

The results are summarized in Table 5.2. Four emulsified fuels with different water contents were used, at 4 engine speeds and 4 loads. The temperature, and carbon monoxide, nitrogen oxides, and soot concentrations of the exhaust at different operating conditions are reported. The exhaust temperature was measured at a distance of 1.3 m from the engine exhaust, thus this temperature was lower than the engine temperature even though the exhaust pipe was well insulated. Figure 5.2 is a schematic of the location of the temperature and gas sampling ports.

The power of the engine was calculated automatically by the control computer according to the following equation:

\[ P = \frac{2\pi nt}{60,000} \]

where \( P \) is the engine power in kW,
\( n \) is the engine speed in rpm,
and \( t \) is the load in Newton-m.

Since the power generated by the engine is dependent linearly on the speed and load, respectively, it is thus proper to study the performance of the engine in terms of emissions, etc., based on the power produced.

Exhaust temperature

Figure 5.3 shows the dependency of the exhaust temperature on engine power for all fuels. The general trend is the larger the engine power the higher is the exhaust temperature, and the same can be extended to the emissions as shall be presented in later sections. Figure 5.4 is the influence of the water content in the fuel on exhaust temperature. By-and-large, when more water was added, the exhaust temperature was reduced further. The existence of water in the engine cylinder required more energy for vaporization, thus it lowered the engine temperature. The exhaust temperature decrease achieved by the emulsified fuels for the same engine power are presented in Figure 5.5. The range of temperature decrease for the 5% fuel is 2 - 34 °C, 4 - 59 °C for the 10% fuel and 6 - 66 °C for the 15% fuel.

A summary of all the changes in the emissions due to emulsified fuels is presented in Table 5.3.

Nitrogen oxides

The lowering of combustion temperature in the engine, as inferred by the lower exhaust temperatures, should inhibit the formation of nitrogen oxides, since a good portion of the nitrogen oxides in combustion processes is the reaction product of atmospheric
nitrogen and oxygen at high temperatures. Figure 5.6 shows the dependency of exhaust nitrogen oxides concentration on engine power. The lowering of nitrogen oxides in the tailgas was quite significant with the largest increment achieved when 5% of water was emulsified in the fuel. As the water content increased, a steady reduction in nitrogen oxides emissions was observed. The range of nitrogen oxides reduction was 3.6 - 29.6%. The single negative change was probably due to instrument or sampling error.

Soot or black smoke

In Figure 5.7 are the results of the soot content in Bosch smoke scale measured in the exhaust when the testbed was subjected to fuels containing various amounts of water. The amount of soot produced decreased when more water was added to the fuel. The biggest reduction in soot formation occurred when 5% of the water was added to the diesel fuel, and the effect was not as pronounced when more water was added. The largest overall soot reduction was achieved at high engine power. The range of soot reduction was 10 - 68%. The details can be found in Table 5.3.

Carbon monoxide

It is expected that with the improvement of combustion in the engine the amount of carbon monoxide produced should be lowered, however, in all most all cases, a substantial increase in carbon monoxide was measured in the exhaust. This can be clearly seen in Figure 5.8 where the relationship between engine power and carbon monoxide concentration is plotted.

One possible reason for the high CO concentration is the reaction between carbon and water vapor outside of the engine when the exhaust temperature is sufficiently high [13]. Examining Figure 5.9, it can be seen that the CO concentration for all fuel huddled around 200 - 700 ppm when the temperature was below 280 °C before increasing quickly. The addition of water in diesel fuel promoted the formation of CO; 10 and 15% emulsified fuels fared the worst. There were two exceptionally high concentrations of CO at 1115 (diesel) and 1960 (10% water) ppm at high exhaust temperatures of 430 and 397 °C, respectively. Take note that these temperatures were measured at a distance from the engine. it is expected that the temperature would be even higher, ~500 - 600 °C upstream of the sampling port. This thermal condition could be conducive in the formation of CO.

The formation of excess CO using emulsified fuels is a disadvantage of this technology because additional CO cleanup is needed. However, on the hand, the existence of CO can be a good energy source for a secondary abatement system such as the catalytic trap incineration method. In such a system, a regeneration step is required to burn off the trapped soot.

5.4.2 Influence of emulsified fuels on the characteristics of soot

Soot or black smoke is a product of combustion process, its characteristics depend on the composition of the fuel used and the combustion conditions. It is expected that with
the addition of up to 15% water in the fuel, some changes in the physical and chemical properties in the soot formed will be observed. The thermal properties were investigated using TG/DSC/MS while the specific surface area of the soot produced was measured using BET.

Soot samples were collected by the filtration of the exhaust gas discharged from the tail-pipe. The engine was operated at 2000 rpm under a load of 170 N-m. Two samples were collected: Soot-0 containing no water and Soot-10 with 10% of water, emulsified.

The burning characteristics of the two soots were studied under the following TG/DSC/MS conditions: temperature increase at 10 °C min⁻¹, the atmosphere was 10% oxygen, balance nitrogen.

The DTG, derivative thermogravimetry curves in Figure 5.10 indicated that Soot-10 experienced the largest weight loss due to combustion at 610 °C, which was 37 °C lower than Soot-0; this suggests that soot produced by emulsified fuel was easier to burn, and would be advantageous to secondary abatement techniques such as catalytic trap incineration. A lower regeneration temperature and lower energy requirement mean it would be easier to burn off the trapped soot. At 500 °C, there is an obvious DTG peak for Soot-0 indicating the existence of low C/H ratio and more combustible hydrocarbons such as unburned fuel or combustion products. The TG curves clearly demonstrate that Soot-10 lost mass faster than Soot-0; at 960 °C, the former lost 96% of its mass while the latter only lost 75%. This suggests that the emulsified fuel was easier and more readily burned.

Examining the mass spectra of the Soot-0 product stream in Figure 5.10, several carbon dioxide peaks are present while only one was found in Soot-10; furthermore, the peaks coincide with the mass loss peaks in DTG. Not much sulfur dioxide was detected indicating the low sulfur content of the fuel or the low absorption of the gas in the soot. Comparatively speaking, the sulfur dioxide in Soot-10 is less, it is possible that this is related to the high water content of the emulsified fuel. There was a gradual decrease in water vapor for the Soot-10 and the change was small in the Soot-0, indicating that the soot from emulsified fuels absorbed much more water.

5.4.2.1 Composition and appearance of the soot produced

The surface of samples Soot-0 and Soot-10 were imaged using SEM and the results are presented in Figure 5.12. The particle diameter in both samples was less than 0.1 μm, however, conglomerates could be as large as 10 μm or larger. The surface of Soot-0 was smooth suggesting the existence of unburned hydrocarbons in liquid phase, on the other hand, Soot-10 was rougher and loose, possibly due to dewatering under vacuum thus leaving openings or cavities on the surface. Using EDAX to measure the abundance of carbon and sulfur contents in the two samples indicated that the carbon in Soot-10 was 1.26 times of that in Soot-0, while the sulfur in Soot-0 was 1.33 times of that in Soot-10. The low sulfur reading could be due to the scavenging by the water in the exhaust.
5.4.2.2 *Specific surface area of the soot produced*

In Figure 5.13 is the BET specific surface area of Soot-0 and Soot-10 when degassed under different temperatures. Both samples exhibited a significant increase in surface area when the temperature was raised. It is known that on the surface of soot particles, there are absorbed, adsorbed and deposited, water, partially burned fuel, unburned fuel, and products. These material can be vaporized as the temperature is increased, leaving behind vacant spaces and sites resulting in more surface area. In the range of 50 to 150 °C, Soot-10 experienced a much bigger change than Soot-0, while above 150 °C it did not change as rapidly as the latter. One possible reason is Soot-10 contained more volatile components such as water as measured by the on-line MS, thus could be desorbed or vaporized at lower temperature, while Soot-0 contained the heavier components of the fuel or incomplete combustion products which needed a higher temperature.

5.4.3 *Fuel consumption and savings*

The fuel consumption and economy using 10% water-diesel emulsion were calculated from the performance data under different speeds and loads, and the results are listed in following Table 5.4.

In all the operating conditions studied, improvement in fuel efficiency was measured, however, the improvement decreased when the load and engine speed were increased. The range of savings was 1.0 to 6.0% while the average increase in fuel efficiency for the conditions studied was 2.9%. The addition of water in diesel improved burning efficiency, however, it decreased the unit energy content in the fuel, which was not favorable when the testbed was operated at high load and speed, in turn, the savings in fuel became insignificant.

5.4.4 *Engine wear due to emulsified fuels*

One of the problems associated with the use of water-emulsified fuel is water corrosion since the water content in the fuel is substantially higher than regular fuel. This is especially important if there is separation of the two phases inside the cylinders. Excessive corrosion will cause accelerated engine wear.

The current emulsified fuel study was carried out on a brand new engine testbed and a wear monitoring program was established to study this phenomenon. Pistons 1 and 3 were carefully measured before and after 300 hours of emulsified fuel operation to determine the wear on the engine. A Profile Projector, PJ-311, Mitutoyo, Japan was used to measure the dimensions of the piston rings, 2 T-rings, and 1 O-ring at three fixed locations L1, L2 and L3 as shown in Figure 5.14. The results are presented in Table 5.5. There was no abnormal wear that could be quantified because of the excessive water present. The piston surfaces were examined under an Olympus microscope and no evidence of rust was detected.
5.5 Road tests

5.5.1 Road Test Vehicle

A diesel passenger sedan, 1985 Isuzu Aska 2.0L, was modified for the emulsified fuel study by adding a second fuel tank in the trunk. A valving system was installed in the fuel line so that either the emulsified fuel mixture or regular diesel fuel could be switched to the engine at will from the driver's seat. The second fuel tank was designed such that the amount of fuel used can be easily and accurately measured. Flush ports were also available so that the tank could be thoroughly cleaned out when different fuel mixtures were used.

The modifications made were trivial with no intention to change the performance of the vehicle; however, during initial tests it was discovered that due to the pressure drop in the plumbing added to the fuel line system, the maximum amount of fuel that could be delivered to the engine was slightly reduced, which meant when the gas pedal was floored the maximum speed obtainable was somewhat lower than before.

A copper sampling tube was also installed so that exhaust samples could be extracted from the tail pipe for smoke intensity analysis when the vehicle was stopped during road tests.

The emulsion was prepared in the laboratory using commercially available diesel fuel and deionized water. A minute amount of hydrocarbon-based stabilizer, supplied by the vendor of the emulsifier was used during blending so that the emulsion could be maintained for a prolonged period of time.

5.5.2 Summary of results

In the current study, the emulsified fuel was tested in the test vehicle on the road for 1000 km. The purpose of this study was to determine the acceptance of the emulsified fuel by vehicle operators, and to see if the soot generated during normal driving conditions could be reduced. The former was a test on the performance of the car as detected by the operator. The performance included acceleration, engine power, smoothness and were qualitative since the operator depended on his feelings, not instruments, to make these judgements. In this study only the mileage, distance per unit weight of fuel was calculated, since this gave a pretty good indication on the performance of the car, and if better mileage could be obtained, the amount of smoke emitted must have been reduced. Tables 5.7 and 5.8 summarize the results of this series of road tests.

The tests were conducted on assigned routes during rush hours but without traffic jam. In all cases, the air conditioner was turned on so that the vehicle was subjected to similar wind resistance at all times.

The impact of traffic condition on fuel economy is rather obvious and significant. For the same road and traffic conditions, using emulsified fuel apparently saved about 8.4% of fuel. This may be taken as an indication of improved combustion in the engine.
The driver reported no significant difference in engine power except that it took a bit longer for the emulsified fuel to warm-up the car when starting on a cold day. Although the vehicle passed government certified smoke test, black smoke was still visible during start-up when regular fuel was used, however, when emulsified fuel was substituted, white smoke, water vapor was seen. This was especially evident in cold weather.

The Environmental Protection Department, EPD made a Hartridge MK3 Smokemeter available for the study. A series of smoke emission measurements were made in the Multi-Storey Car Park at the University. The test procedure used followed that currently employed by EPD in their Smoke Detection Centre.

One of the tests, Test 2 was conducted on January 15, 1993, a particularly cold day, 10°C, to see if the low ambient temperature had any influence on the outcome of the results. The results of the study are presented Table 5.9.

These tests suggest that the emulsified fuel reduces the soot or smoke emitted from diesel vehicles at no obvious penalty in the performance of the vehicle. As a matter of fact, there was improvement in fuel economy. Although these tests were made when the vehicle was running idle, taking the results of the road tests into consideration, it is safe to say that the water/diesel emulsified fuel used can reduce smoke emitted from diesel-powered passenger sedans.

5.6 Conclusions

The use of water-emulsified diesel fuel as a measure in the reduction of soot or black smoke in automobile exhaust was studied in the laboratory and on the road. The results were mixed in that substantial reduction in soot, 10 - 68% in testbed, 36% in road tests and nitrogen oxides, 3.6 - 29.6% in testbed could be achieved, however, the CO concentration increased from 8.3 - 12.5%. There was also a savings in fuel consumption at 1 - 8%. The reduction in soot emission is probably insufficient to meet the requirement to clean up the atmospheric aerosol issue. This suggests that a secondary is needed to further reduce the soot emission and CO cleanup. This is consistent with previous findings that no one currently available technology is capable of controlling diesel emissions satisfactorily [3-6].

The soot formed using emulsified fuels was found to burn more easily and at a lower temperature, because the soot formed contained less residues. This property is advantageous to secondary abatement systems such as a catalytic trap incineration system, where a regeneration step is needed to burn off the trapped soot.

Engine wear measurements after 300 hours, equivalent to 15,000 km of emulsified fuel operation showed not abnormal wear, suggesting that the excess water in the fuel did not promote corrosion in the engine.
Acknowledgments

The invaluable assistance provided by Mr. S.K. Lee and his staff of the Department of Mechanical Engineering, and staff of the Materials Preparation and Characterization Facility is deeply appreciated. We also indebted to the Department of Mechanical Engineering for jointly developed the engine testbed facility.

We are grateful to EPD for their support of this project in the form of lending us a Hartridge MK3 Smokemeter.

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References

(1) -, 1992 Air quality in Hong Kong 1992, Air Services Group, Environmental Protection Department, Hong Kong Government.


(9) Murayama, T., Tsukahara, M., Morishima, Y., "Experimental reduction of NOx, smoke, and BSFC in a diesel engine using uniquely produced water fuel, zero to 80% emulsiton", SAE-T 78 0224.


(16) Ingham, M.C., and Warden, R.B., SAE Paper 87 0556.


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<th>Specification</th>
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<td>Fuel system</td>
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*1 kW = 1.34 hp

Table 5.1 Diesel engine specifications
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Table 5.2 Impact of emulsified fuels on exhaust emissions
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*Note: % change =, \( \frac{N_{No\,water}}{N_{water}}N_{No\,water} \times 100

Table 5.3 Change in emissions due to emulsified fuels

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*The numbers in, are the diesel in the emulsion.

Table 5.4 Fuel consumption and economy using emulsified fuels
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<tr>
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<th>T-ring 1</th>
<th>T-ring 2</th>
<th>O-ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, mm</td>
<td>L1</td>
<td>L2</td>
<td>L3</td>
</tr>
<tr>
<td>After 300 hr of operation</td>
<td>3.524</td>
<td>3.546</td>
<td>3.565</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Piston 3</th>
<th>T-ring 1</th>
<th>T-ring 2</th>
<th>O-ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, mm</td>
<td>L1</td>
<td>L2</td>
<td>L3</td>
</tr>
<tr>
<td>Initial</td>
<td>3.422</td>
<td>3.559</td>
<td>3.539</td>
</tr>
<tr>
<td>After 300 hr of operation</td>
<td>3.417</td>
<td>3.555</td>
<td>3.537</td>
</tr>
</tbody>
</table>

Table 5.5 Wear data of pistons after 300 hours of operation

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition, % by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>10</td>
</tr>
<tr>
<td>Emulsifying agent</td>
<td>0.8</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 5.6 Composition of emulsified fuel

<table>
<thead>
<tr>
<th>Traffic condition</th>
<th>Regular fuel</th>
<th>Emulsified fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rush hour</td>
<td>Rush hour</td>
<td>Free flowing</td>
</tr>
<tr>
<td>Distance, km</td>
<td>631</td>
<td>222.3</td>
</tr>
<tr>
<td>Fuel economy, km/kg net fuel</td>
<td>13.1</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Table 5.7 Fuel economy
<table>
<thead>
<tr>
<th></th>
<th>Regular fuel</th>
<th></th>
<th>Emulsified fuel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak</td>
<td>Steady-state</td>
<td>Peak</td>
<td>Steady-state</td>
</tr>
<tr>
<td><strong>Test 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>33</td>
<td>27</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>33</td>
<td>33</td>
<td>23</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>33</td>
<td>30</td>
<td>24</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>33.8</td>
<td>24.5</td>
<td>20.3</td>
<td>15.3</td>
</tr>
<tr>
<td><strong>Improvement</strong></td>
<td></td>
<td></td>
<td>40%</td>
<td>37%</td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>38</td>
<td>27</td>
<td>24</td>
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<td>38</td>
<td>35</td>
<td>30</td>
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<td>35</td>
<td>35</td>
<td>29</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>38</td>
<td></td>
<td>29</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>35.5</td>
<td>29.3</td>
<td>22.7</td>
<td>19.0</td>
</tr>
<tr>
<td><strong>Improvement</strong></td>
<td></td>
<td></td>
<td>36%</td>
<td>35%</td>
</tr>
</tbody>
</table>

Table 5.8 Smoke measurements
V1 water shut-off valve  
V2 diesel inlet valve to emulsifier  
V3 diesel shut-off valve  
V4 water flow rate control valve  
V5 check valve  
V6 emulsifier inlet pressure regulating valve  
V7 emulsion recycle valve  
V8 emulsifier discharge shut-off valve  
V9 emulsifier discharge pressure control valve  
Tw water temperature indicator  
Td diesel temperature indicator  
P1 inlet pressure indicator, 0-600 psi  
P2 outlet pressure indicator, 0-300 psi  
P3 discharge pressure indicator, 0-300 psi

Figure 5.1 Emulsifier system flow diagram
Figure 5.2 Engine testbed sampling locations

Figure 5.3 Relationship between exhaust temperature and engine power
Figure 5.4  Dependence of exhaust temperature on engine power using emulsified fuels

Figure 5.5  Temperature decrease achieved by emulsified fuels
Figure 5.6 Influence of water in fuel on NOx emission

Figure 5.7 Influence of water content in fuel on soot production
Figure 5.8 Influence of water content in fuel on CO emissions

Figure 5.9 Influence of temperature on CO emissions, all fuels
Figure 5.10 Thermal analysis for Soot-0 and Soot-10 in 10% O₂/N₂
Figure 5.11 Mass spectra of combustion products
Soot from fuel without any water emulsified.

Soot from 10% water emulsified fuel

Figure 5.12  SEM images of Soot-0 and Soot-10, x14,000
Figure 5.13  Specific surface area of soots

Figure 5.14  Engine piston and ring measurement positions
Chapter 6 Abatement of particulate emissions from diesel-powered engines - A review

6.1 Introduction

According to the 1989 Government White Paper on the environment, suspended particulate matters is one of most serious pollution problems in Hong Kong. Government figures show that about 44% of the airborne particulate matters is emitted by diesel-powered vehicles.

The widespread use of diesel-powered vehicles in Hong Kong is because diesel engines have high thermal efficiency and are more lax on fuel requirements. Both of these factors translate into better fuel economy.

From the emissions point of view, diesel engines when compared to gasoline-powered engines, discharge less light hydrocarbons and carbon monoxide, however, they emit substantially more, 30 to 100 times more, particulate matters and nitrogen oxides [1].

Diesel engine particulates are basically carbonaceous agglomerates, with higher molecular weight organic substances absorbed or condensed on them, as well as sulfates and trace metals [2]. The absorbed organic compounds are partially oxidized hydrocarbons, phenols and polycyclic aromatic hydrocarbons (PAHs). Some of these compounds are known to be carcinogenic [3]. It has been established that 90% of the particulate matters emitted by diesel engines consists of particles less than 1 μm in diameter, well within the respirable range and is potential health hazard [4].

In addition to the pollutants adhered onto the surface of these particulates during formation, the trace metals can also act as catalyst and promote chemical reactions once airborne. This synergistic effect is especially hazardous to the environment.

The environmental impact of diesel exhaust is numerous. The unpleasant smell caused by oxygenates is very familiar to citizens of Hong Kong. Besides reducing visibility, the particulate matters can also be carcinogenic as well as soil clothings and properties. Previous studies carried out in London to correlate cancer statistics of taxi drivers and other diesel-powered vehicle operators, indicated an increase in occurrence of bladder cancer. A US study of railroad workers who were exposed to diesel exhausts, suggested that they stand a 42% greater chance of developing cancer than those not exposed. In another study of retired railroad workers, an association was found between lung cancer and exposure to diesel exhaust [5]. Diesel engine exhaust particles can also cause non-cancer related diseases [6].

Hong Kong already has legislation to deal with tailgas emissions from gasoline-powered vehicles, and is in the process of establishing emission standards for diesel-powered vehicles. This article reviews some of the available technology in abating particulates emitted by diesel-powered engines.
6.2 Formation and genesis of diesel particulates

One of the products of combustion processes is particulate matters. It is known that soot will form in a combustion chamber when the temperature (2000 K) and pressure are high, and/or the fuel to air ratio is too rich [79]. The formation of these particles can be broken down into three consecutive stages, although all these processes may occur simultaneously during a given combustion process [6,10]: crystallite (embryonic nuclei) formation, aggregation (prime particle formation) and agglomeration (soot chain formation).

Right after the ignition of injected fuel in a combustion chamber, unburned fuel and lube oil hydrocarbons are present due to incomplete combustion. There are also partially oxidized products. In the most oxygen deficient regions of the flame, the fuel hydrocarbons undergo a series of chemical transformations, during which the hydrogen to carbon ratio decreases to the extent that soot precursor molecules (saturated platelet) and subsequently embryonic nuclei of 0.001 - 0.01 µm in diameter are formed.

These soot nuclei undergo first coalescence to form primary particles with diameters of the 0.01 - 0.05 µm range. These primary particles form soot particles through chain forming coagulation [4,8,10,11]. The coagulation of primary particles may be accompanied by the sorption or condensation of sulfates, fuel and lube oil hydrocarbons, which can, in the interim, be transformed into a variety of polycyclic aromatic components (PAHs).

Diesel particulates consist of organic and inorganic components in solid and liquid phases [10,12]. See Table 6.1. Usually they contain 20 - 40 weight % of hydrocarbons [13], but can vary in the range of 1-90 weight %, depending on the engine type and driving conditions [13-17]. The sulfate content in these particles ranges from 1 to 2 weight % due to the 0.21 to 0.24 weight % sulfur fuel typically used today [18]. Table 6.2 shows typical elemental compositions of diesel particles.

In addition to the formation of particulate matters during the combustion process, particles in the form of ammonium sulfate and nitrate are also formed due to the reaction of emitted gaseous components such as sulfur dioxide and nitrogen oxides with oxygen, ammonia and water in the atmosphere. Essentially all the sulfur in the fuel is converted to sulfur dioxide during combustion adding another 20 weight % to the sulfate particles already formed [19].

6.3 Impact of diesel emissions on the environment

The most obvious effect of diesel emissions is probably the unpleasant smell caused by the oxygenates when a big truck drives by you. On roads with heavy traffic, such as Waterloo Road near the Lion Rock Hill Tunnel entrance, the haziness is caused by the particulate matters emitted from road vehicles. It has been recognized that diesel particulates having small diameters, white smoke, are often more dangerous because they are respirable and are carcinogenic in many instances. Respirable particles, as defined by the
Environmental Protection Department, are "suspended particles in air with a nominal aerodynamic diameter of 10 micrometers and smaller". Respirable particles can enter into lung alveoli and the process is irreversible.

The link between diesel exhaust and cancer and other diseases in human has long been studied and the details can be found in various reports [5,6].

6.4 The abatement of particulate matters emitted from diesel engines

The technology and methods used to reduce diesel particulates are based on our knowledge of the formation of these matters, namely "inside engine measures" and "outside engine treatment". Several of the most popular technology will be discussed in the following sections.

6.4.1 Inside engine measures

As a rule, inside engine measures are the most desirable means because they not only reduce pollution but also improve fuel economy, although in many cases, inside engine measures may not be sufficient to meet the ever stringent emission standards.

6.4.1.1 Engine modifications

The following list contains some of the most popular methods investigated:

(1) Modification of combustion system (e.g. new combustion chamber design) [20,21].
(2) Changes in fuel injection system (e.g. improvement of injection nozzle and injection pump, electronic control or regulation of injection begin and quantity) [22-25].
(3) Adoption of exhaust turbocharger [26,27].
(4) Exhaust gas recirculation (EGR) [28-30].
(5) Lubrication oil control [31,32].

It is expected in the next few years major engine improvements can be realized resulting in reduced emissions. However, it is not obvious that the emission targets can be met by engine design modifications alone.

Exhaust gas recirculation can reduce NOX emission at a penalty of increased particulates formation. It is estimated that a reduction in 50 % in NOX could cause more than 100 % increase in particulates [29]. This conflict between the amount of NOX and particulate emitted is due to the inherently thermal conditions of combustion processes.

6.4.1.2 Fuel reformulation

From the material balance point of view, the quality of fuel used is paramount to the makeup of engine emission. Cleaner fuels under proper operating conditions usually means less pollution and the reverse is usually true.

Diesel fuel reformulation involves the following components of the fuel: sulfur content, aromatics and cetane number. Sulfur and aromatics must be minimized to reduce pollution. To guarantee reliable ignition, which in turn affects emissions, the cetane number must be maintained at the correct level.
Aromatics are hydrocarbons with dense structures and have poor ignitability thus are responsible for smoky flames in combustion. Studies showed that by lowering the aromatic content of a fuel from 29 %, which is about average for today's diesel fuel, to 17 %, a reduction of about 30 % in particulates can be achieved in the exhaust. About 15 % reduction in hydrocarbons and 8 % in NOx are also experienced [33].

The decrease in aromatics leads to an increase in cetane index and the cold starting behaviors can also be significantly improved. The cold starting characteristics is closely related to the gaseous emissions. In addition, it has been proven that the mutagenic activity of soluble extracts from soot particulates is lower in lower aromatic fuels [34].

The role of sulfur in the formation of primary and secondary particulate matters has already been discussed earlier. In addition, sulfur in fuel cannot be reduced or rendered harmless by improved combustion (engine modifications) and other internal measures [35].

Experimental results taken from [1] indicate that a decrease of fuel sulfur content from 0.25 % to 0.05 % can lead to a reduction of 81 % in sulfate particles generated, 80 % in secondary sulfate particles, and 70 % in total particulates. On the other hand, a decrease in aromatics from 32 % to 10 % amounts to 28 % reduction in carbonaceous particles and 4 % in total particulates. Thus, the effect of sulfur on particulates formation is significantly more important than that of the aromatic compounds.

Sulfur is a known poison to a variety of catalysts, its presence can prevent the adoption of catalytic technology in tailgas cleanup catalytic systems.

6.4.1.3 Alternate fuels (non-fossil based)

Currently there is a lot of interest in using alternate fuels such as natural gas [36], alcohols [19, 37-39], or esters as automotive energy source. These alternate fuels are also cleaner in the environmental sense [40]. However, unlike the gasoline-powered engines, current diesel technology cannot take advantage of these developments, additional steps or modifications are needed for using alcoholized fuels in diesel engines. In Table 6.3 are some results from a study on the emissions from several methanol-powered engines and a typical diesel engine [19].

It can be seen that significant reduction in pollution can be achieved by using methanol as fuel, however, methanol is a very toxic material and can be fatal when ingested [41]. In addition, one of the products of methanol combustion is formaldehyde and therefore ozone formation. This is an environmental hazard when sufficient quantity of this fuel is used in the future, thus a separate formaldehyde emissions standard is also promulgated [35].

6.4.1.4 Diesel exhaust gas after-treatment

6.4.1.4.1 Particulate separator

The fundamental concept of this method is to remove diesel particulates from exhaust gas by suitable separators for subsequent regeneration by periodic burn-offs either in situ or outside of the separator. This technique seems to be the most practical solution for
meeting emission standards (particulates and NO_x) before other advanced control
technology can be fully developed.

Examples of this class of device are: cyclones, exhaust gas washers, electrostatic
precipitators, and filters.

There are two important parameters used in the characterization of separators:
separation efficiency and flow resistance. Other requirements when considering separators
are small volume, high mechanical and thermal strength, and low cost.

Separation efficiency, h, is defined as the ratio of the difference between the inlet
and outlet particles mass flow rates and the inlet particles mass flow rate. Because of the
dependency of particle emission on vehicle weight, different separation efficiencies are
required for vehicles of different weights. For example, a 1134 to 1588 kg weight vehicle
requires a separation efficiency of 35 - 80 % to meet the 0.1243 g km\(^{-1}\) particulate emission
limit and 0.6123 g km\(^{-1}\) NO_x emission limit for 1987 model year American cars [42].

The use of separators poses a penalty in increased back pressure which in turn
decreases fuel efficiency. Studies [4] indicate that for a midsize car (1360 kg), each 1 mbar
increase in exhaust back pressure can lead to an additional fuel consumption of 0.03 %.

6.4.1.4.1.1 Exhaust gas washer

The removal of solids from a gas stream by means of washing or scrubbing is a
common practice for stationary sources, however, when used on diesel vehicles the
requirements for size and additive consumption rate are far too large for a desired efficiency
[43].

6.4.1.4.1.2 Cyclone

The effect of a cyclone is based on the mass force of the matters to be separated. It
was shown [44] that the efficiency of cyclones in removing particulates from vehicular
exhaust can reach a mere 6 % with the best cyclone designs because of the size distribution
and the smallness of the particles.

6.4.1.4.1.3 Electrostatic precipitator

An electrostatic precipitator used in vehicular exhaust particulate removal comprises
of an electrostatic agglomerater and a cyclone [45-48]. A dramatic improvement of
separation efficiency can be achieved by this combination. For instance, a removal level of
80 % in stationary operation and 50 % in a FTP driving cycle can be reached [46].

In order to remove the particulates collected in the cyclone, the collected particulates
are recycled into the engine together with the exhaust gas recirculation for burn off in the
combustion chamber [46, 49, 68]. However, there are many problems associated with this
technology including incomplete combustion, enrichment of sulfates, ash, and abrasion.

6.4.1.4.1.4 Particulate filters

Filtering can be very effective in removing particulate matters in exhaust streams
and there are four different types of particulate filters in use: modified monolithic ceramic
filters [42, 51] made from honeycomb ceramic substrate used in gasoline engine catalytic converters, metallic fiber filters [52], ceramic foam filters [53], and ceramic fiber coil filters [54, 55].

Mechanical filtration mechanisms consist of impaction, accumulation and diffusion [42]. Impaction and diffusion are the principal mechanism of separation in deep bed filters such as metallic fiber and ceramic foam filters. The larger particles collide on the threads of the filter fiber and can either stick onto the thread surface, or are accumulated on previously collected particles. Smaller particles are collected on the filter surface by diffusion.

Accumulation is the dominant mechanism for shallow bed filters such as monolithic ceramic filters and ceramic fiber coil filters. Particles with diameters larger than the mean pore size of the filter medium will be retained and a layer is built up on the surface. The effective pore size decreases when the particulates accumulate on the surface of the filter, resulting in an increase of filtration efficiency however there is an increase in pressure drop. Monolithic ceramic filter

Monolithic ceramic filters are the most effective and most investigated filter used for abating diesel particulates. They consist of square-shaped cells with parallel channels running along the length of the cells. The walls of these cells are porous allowing them to be used as filters. Alternate ends of adjacent cells are plugged with a ceramic material forcing the gas to flow through the porous walls. Particulate matters are collected on the porous walls as the exhaust gas passes through. The number of cells per cross-section of the filter, known as cell density, determines the surface area available for filtration which in turn determines the flow resistance of the filter. However, a high cell density will lead to a high axial flow resistance in the channels because of the decrease in hydraulic diameter [18]. The filtration efficiency can be increased by decreasing the pore size, but the increase in flow resistance can be prohibitive.

In practice, a cell density of 15-30 cells cm⁻² (100-200 cells in⁻²) [42, 56, 57] and a mean pore size of about 12.5 mm [56] are used. A filtration efficiency of 60-95 % can be reached with this type of device [42, 51, 56-58].

Ceramic fiber coil filter

Ceramic fiber coil filter consists of a filter core made up of a bundle of bored steel tubes, around which temperature resistant ceramic yarn is wound. The exhaust gas flows from the outside into the inside of the tubes, as a result, the soot and other particles are collected on the surface of the ceramic fiber [59]. In comparison to monolithic ceramic filters, coil filters have about the same efficiency [54, 59] but a more rapid increase in back pressure [55].

Ceramic foam filter

Ceramic foam filter is different from ceramic monolith in that its filtration efficiency is determined by the filter length and pore structure. By changing the length and the pore
structure the filtration efficiency can be adjusted in a range of 60 to 80 % [60, 61]. Despite of its lower filtration efficiency, ceramic foam filters are more fuel efficient because of its smaller pressure drops.

In comparison to ceramic monoliths, one disadvantage becomes apparent: because of the structure of the material, collected material can be blown off when the exhaust flow rate increases as in the case of increased engine loading.

**Metallic fiber filter**

The main part of a metallic fiber filter is a hollow cylinder made of metallic fibers, which is coated with an aluminum oxide washcoat and impregnated with a precious metal catalyst. The catalyst is used to oxidize the high boiling hydrocarbons in soot particles thus promoting the ignition of particles themselves. The filtration efficiency of the metallic fiber filter amounts to only 40 to 60 % [26, 81]. Other advantages and disadvantages are the same as those of the ceramic foam filter.

6.4.1.4.2 **Regeneration of particulate filter**

Previous investigations, as mentioned above, indicate that substantial removal of particulates from diesel exhaust can only be achieved by filtering techniques, in particular, using shallow bed filters. The most important issue in using this technology is the regeneration of the filters after particulates are trapped. This is needed because of the build up of back pressure as the particulates accumulate resulting in severe penalty on fuel economy.

The regeneration frequency, the number of regeneration per time unit or per driving distance, required depends not only on particulate concentration which is a function of engine type and driving conditions, but also on the filtration efficiency of the filter. Because of the high increase rate of back pressure, a higher regeneration frequency is usually required for shallow bed filters.

Self regeneration is not possible because of the high ignition temperature of diesel soot, typically 500 - 650 °C [60, 64-66], and low exhaust temperature (around 300 °C) [67], therefore some external energy or means is needed to get rid of the trapped particles. The two methods commonly used to initiate the regeneration process are by increasing the exhaust gas temperature, and by reducing the soot ignition temperature.

The exhaust temperature can be raised by applying external energy, e.g. using burners or electrical heaters, or by reducing the gas flow rate such as inlet air or exhaust throttling.

Lowering soot ignition temperature can be achieved by three methods: adding organometallic compounds to the fuel, injecting metal-containing boosters into the exhaust or onto the soot layer in the filter, and coating the filter with a soot combustion catalyst.
6.4.1.4.2.1 Regeneration by Increasing Exhaust Gas Temperature

**Burner**

The principles of burner systems [42, 63, 66, 68] is shown in Figure 6.1. The burner can be aspirated with exhaust gas or air. If burner can be operated either in-line or on the bypass, the latter is for preventing the filter from overheating during the combustion of soot deposits.

An additional 2.5 to 5 % fuel is needed to operate the burner and there are other factors to consider:

1. Homogeneous spreading of the flame in the radial direction.
2. Reliable ignition of fuel/air (or exhaust gas) mixture.
3. Proper extend of temperature increase in order to avoid too high a thermal stress in the filter.

**Electrical heater**

In regeneration systems using electrical heaters [63, 64, 68-70], an exhaust gas slip-stream is used so that the energy from the battery and generator is sufficient to initiate a combustion, see Figure 6.2. The effectiveness of the regeneration is a function of the amount of soot to be burned, the duration of electrical heating, and the flow rate of exhaust gas through the filter.

During regeneration, particulates accumulated near the heating elements will be ignited first spreading the combustion throughout the rest of the filter. If the heating is in a soot loading area too low to sustain combustion, then the spread of the combustion throughout the rest of the filter may not be guaranteed. Conversely, if the loading is too high, the combustion temperature may be higher than the melting point of the filter material causing permanent damage. The same phenomenon will occur if the flow rate of the slip stream of the exhaust gas is too small. Usually there is insufficient spread of combustion in the radial direction and there is also a fuel penalty of about 3.5 %.

**Exhaust gas throttling**

An exhaust gas throttling regeneration system [71-74] is schematically represented in Figure 6.3.

In the case of no exhaust gas throttling, the engine back pressure is due to the drop across the filter. An increase in back pressure will be experienced if either the inlet or outlet of the exhaust is restricted, forcing an increase in the engine load which in term raises the exhaust temperature to a point that regeneration can be started.

The additional fuel consumption required in exhaust gas throttling is about 1%.

**Inlet air throttling**

The exhaust gas temperature can also be raised by adjusting the flow rate of air fed into the engine. With this adjustment of the air/fuel ratio the exhaust gas temperature can be raised to 650 °C to facilitate regeneration. However, this temperature increase is
accompanied by an increase in exhaust emissions. During the throttling operation, oxygen in the exhaust is reduced by 25 % and higher particulate emission has been observed [42]. Thus there is a limit as how much inlet air throttling can be allowed before too big a penalty is paid.

6.4.1.4.2.2 Regeneration by raising temperature of soot deposit

**Microwave heating**

Recently, a new auxiliary heating technique, microwave heating, has been developed [75-79]. Figure 6.4 shows a particulate filter regenerations using such technique as energy source [75].

The apparatus comprises a metal reaction housing, a non-microwave absorbing honeycomb ceramic filter coated with catalyst (K₂CO₃), a set of metal net for shielding microwave before and after the filter, a set of temperature measuring devices outside of the net, a microwave output control circuit, and a magnetron.

In this system, carbonaceous matter absorbs microwaves from the magnetron and then is heated up to its burning point. It has been demonstrated, for example, if 15 g of carbon is loaded on a 2.3 liter ceramic filter with catalyst coating, the filter can be cleaned up with a microwave irradiation of 200 W within 3 minutes [75]. Microwave heating system has the lowest power consumption of any system for burning soot [79].

4.1.4.2.3 Regeneration by reducing soot ignition temperature

**Catalytic coating**

It is known that the ignition temperature of carbonaceous matters can be reduced in the presence of metals such as Pb, V, Cu [80, 81], and based on the experience in gasoline-powered engine catalytic converters, many investigations have been carried out using catalytic techniques to regenerate diesel exhaust filters.

One of the largest catalytic converter manufacturers developed a diesel filter made of metallic fiber on which precious metal catalysts are coated [52]. With this catalytic trap oxidisers, the gaseous emissions and the high boiling hydrocarbons bounded on the particles can be oxidized under normal exhaust gas temperatures, and the remaining "dried" carbonaceous particles can be burned off by the catalyst promoted by the thermal energy released during the oxidation. However, the results obtained so far indicate that only an 25 to 60 % reduction of particulates can be achieved, and in addition, because of effectiveness of the precious metal catalysts on the oxidation of sulfur dioxide to sulfur trioxide, an increase in sulfates is also observed.

It has been shown that using precious metals alone has only a modest effect on the lowering of soot ignition temperature (less than 70 °C), however, if non-precious metals such as the transition metals and a combination of the two is used, the ignition temperature can be reduced to below 400 °C [82, 62, 64, 83-89]. In the latter case, it is possible to
lower the ignition temperature while simultaneously maintaining the oxidation of CO and HC [73, 83].

**Fuel with additives**

Organometallic compounds can be used as additives in fuels to lower the ignition temperature of soot. The metals are finely distributed on soot after combustion in the engine. This improves the contact between metal oxides, which serve as catalysts, and soot particulates significantly. It has been shown that the ignition temperature of soot can be reduced to 280-400 °C, when Cu, Mn, Ce, Fe, Ni, Pd, Zn and Ca are used in fuels [87, 90-93]. Comparing to catalyst coating on filters using the same metals, fuel additive technique is more effective in reducing soot ignition temperature [93].

The biggest disadvantage of this technology is the possibility of creating secondary pollution caused by the uncollected metal particles, even if monolithic ceramic filters with high collection efficiency are used to collect the particulates. There will also be a buildup of metal oxide ash layer on the filter.

**Injection of catalytic solution**

There are other problems associated with fuel additive techniques: first, the additive may deposit on the wall of the engine pistons deteriorating engine performances; second the additives are fed into the engine regardless whether regeneration is necessary or not, and whether the conditions for regeneration is suitable or not. One method to circumvent these is direct additive injection.

In the direct injection method, the catalytic solution can be injected either into the exhaust gas stream or onto the soot layer on the filter surface [64, 65, 85, 94-96]. Thus the injection timing and amount can be selected based on a predetermined control scheme, and as low as 300 °C ignition temperature is possible with this method. However, the secondary pollution problem described earlier is still valid with this method.

**6.4.1.4.2.4 Combined regeneration systems**

Based on the current state of technology, it is realized that any one single measure will not satisfactorily provide reliable regeneration under common driving conditions, instead, a combination of these methods mentioned above is needed. The combination of catalytic techniques, for reducing ignition temperature of carbonaceous materials, with a exhaust gas temperature raising technique will probably be a more effective means. Some other combinations are listed as follows:

1. Exhaust throttling with additives.
2. Throttling with catalyst coated filters.
3. Catalyst coated filters with microwave heating.
4. Catalyst coated filters with oxidative solution injection.

Table 6.4 lists some of the commercially available particulate filter regeneration systems.
6.4.1.4.2.5 Flowthrough diesel catalytic converter

The greatest difference between emissions from gasoline-powered vehicles and diesel engines lies in the particulates. It is also known that diesel particulates consist of not only carbonaceous matters but also liquid organic compounds. The latter really is the threat to health because of its carcinogenic properties. Recent advances in diesel engine technology have greatly reduced the formation of particulates. However, the particulates emitted from such improved diesel contain even more soluble organic fraction, SOF. Something needs to be done to abate the SOF from these engines. Borrowing from gasoline-powered vehicle experience once more, flowthrough catalytic converters have been developed which require no regeneration and virtually have no back pressure.

The standard practice in gasoline-powered vehicle tailgas treatment is to utilize a noble metal catalyst supported on a flowthrough ceramic monolith. Although such a catalytic converter is effective for the oxidation of SOF, HC and CO, it also oxidizes SO₂ to SO₃ resulting in the formation of significant amounts of sulfate containing particulates [99]. Thus the technical challenge is to formulate an oxidation catalyst which is capable of selectively oxidizing carbon containing components at low exhaust gas temperatures typical of diesel exhaust, and at the same time does not oxidize sulfur dioxide or nitrogen oxide in this temperature range [10].

The operating principles of a diesel flowthrough catalyst converter is shown in Figure 6.5.

The features of the device are as follows [38, 100]:

1. A tortuous exhaust flow path to improve the contact between the portion of organic particulate possessing the right mass and momentum and the catalyst surface.

2. A catalyst substrate with low thermal inertia to improve the adsorption and reaction of the organic particulates.

3. Using a noble metal which does not oxidize sulfur dioxide by adopting the following rules:
   - Pd for hot, greater than 300 °C, applications,
   - Pd or Pt for cooler applications.

4. Using a catalyst substrate material which does not store or release sulfur during temperature transients.
References

(1) Ingham, M.C., and Warden, R.B., SAE Paper 87 0556.
(9) Uyehara, O.H., SAE Paper 80 0969.
(33) Barry, E.G., et al., SAE Paper 85 0278.
(44) Spinger, K.J., and Stahlmann, R.C., SAE Paper 77 0716.
(45) Lowi, A.Jr., SAE Paper 84 1398.
(49) Gibbs, R., et al., SAE Paper 86 0291.
(51) Howitt, J.S., SAE Paper 81 0114.
(52) Enga, B.E., et al., SAE Paper 82 0184.
(53) Takama, K., et al., SAE Paper 84 1394.
(64) Niura, Y., et al., SAE Paper 86 0290.
(70) Huethwohl, G., et al., SAE Paper 87 0017.
(72) Pattas, K.N., et al., SAE Paper 86 0293
(74) Pattas, K.N., et al., SAE Paper 90 0109.
(82) Abthoff, J., SAE Paper 85 0015.
(90) Wiedemann, B., and Neumann, K.H., SAE Paper 85 0017.
(93) Ma, Jianxin, Hoffmann, U., Huadong Huagong Xueyuan Xuebao, in press.
(95) Hardenberg, H.O., et al., SAE Paper 87 0180.
<table>
<thead>
<tr>
<th>Solid</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic</td>
<td>Soot, solid hydrocarbons</td>
</tr>
<tr>
<td>Inorganic</td>
<td>Ash from fuel additives, rust particles, sulfates, metal chips</td>
</tr>
</tbody>
</table>

Table 6.1 Phase composition of diesel particles

<table>
<thead>
<tr>
<th>Elements</th>
<th>Content (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>70 - 90</td>
</tr>
<tr>
<td>H</td>
<td>0.4 - 2.0</td>
</tr>
<tr>
<td>O</td>
<td>up to 20</td>
</tr>
<tr>
<td>N</td>
<td>up to 1</td>
</tr>
<tr>
<td>S</td>
<td>1 - 4</td>
</tr>
<tr>
<td>Ash</td>
<td>0.6 - 2.0</td>
</tr>
</tbody>
</table>

Table 6.2 Elemental compositions of diesel particles
<table>
<thead>
<tr>
<th>Engine</th>
<th>San Francisco</th>
<th>Jacksonville</th>
<th>Typical diesel engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>6V-92TA</td>
<td>GM1 D2564</td>
<td>Rebuilt 6V71</td>
<td>6V71</td>
</tr>
<tr>
<td>Oxidation catalyst</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

| Emissions (g/bhph) | | | | | | |
|-------------------|--|--|--|--|---|
| HC                | 1.28 | 0.07 | 10.4 | 5.2 | 0.4 - 0.6 |
| CO                | 1.31 | 0.28 | 79.1 | 12.3 | 2 - 3 |
| NOx               | 2.20 | 5.75 | 1.7  | 2.1  | 5 - 9 |
| Particulates      | 0.17 | 0.018 | 0.17 | -   | 0.5 - 0.6 |

1General Motors.

Table 6.3 Emissions from methanol-powered engines

<table>
<thead>
<tr>
<th>System</th>
<th>Country</th>
<th>Regeneration technique used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donaldson Co. Inc.</td>
<td>US</td>
<td>Electrical regeneration bypass system</td>
</tr>
<tr>
<td>ELBO</td>
<td>Greece</td>
<td>Exhaust gas throttling with fuel additive</td>
</tr>
<tr>
<td>Zeuna Starker</td>
<td>Germany</td>
<td>Burner system</td>
</tr>
<tr>
<td>Kador</td>
<td>Chile</td>
<td>Exhaust throttling</td>
</tr>
<tr>
<td>Detroit Diesel/</td>
<td>Canada</td>
<td>Burner system</td>
</tr>
<tr>
<td>ORTECH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voestalpine</td>
<td>Austria</td>
<td>Electrical igniter</td>
</tr>
<tr>
<td>IVECO</td>
<td>Italy</td>
<td>Burner system</td>
</tr>
<tr>
<td>Volvo</td>
<td>Sweden</td>
<td>Electrical igniter</td>
</tr>
<tr>
<td>Webasto</td>
<td>Germany</td>
<td>Burner system</td>
</tr>
<tr>
<td>MAN</td>
<td>Germany</td>
<td>Burner system</td>
</tr>
<tr>
<td>Mercedes</td>
<td>Germany</td>
<td>Catalyst injection</td>
</tr>
<tr>
<td>CATTRAP</td>
<td>Canada</td>
<td>Catalyst coated filter</td>
</tr>
</tbody>
</table>

Table 6.4 Commercially available smoke trap systems [35, 97, 98]
Figure 6.1 Particulate Trap System with burner as heating element

Figure 6.2 Bypassable trap with an electrical regenerator
Figure 6.3 Throttling regeneration system

Figure 6.4 Microwave particulate regeneration system
Figure 6.5 Flowthrough catalytic incinerator
Appendix 1

List of publications


II Standard operating procedures for the 4D68 Mitsubishi engine testbed

Starting the diesel engine
(1) The chilling water to the radiator must be turned on. After turning on the valve, make sure there is chilled water flowing through the engine testbed at a flow rate to keep the water temperature \(<60\, ^\circ\text{C}\).
(2) Turn on the main power switch, 20A SPN Isolator of the testbed located in the engine room.
(3) Turn on the dynamometer control, computer located in the control room. This includes booting the computer and the control board, see TS-135 Manual.
(4) Switch on the 24V power located in the control room.
(5) Check the fuel tank to make sure it is filled with the correct fuel.
(6) Open the diesel oil supply inlet and return valves located in the engine room.
(7) Adjust the engine speed using the 15-turn fuel micrometer needle valve to about 4 divisions on the micrometer.
(8) Use the ignition key to turn on the engine. Stop first at the "load" position. The symbols of oil tank, battery and oil pump will all light up on the display screen.
(9) Then turn to the "start" position and hold to crank the engine. Once the engine has been started, release the key and allow it to return to the "load" position.
(10) The engine is now running at idle conditions. About 5 minutes are needed for the engine to warm before the engine is ready for accelerating and loading.
(11) Perform experiment as appropriate. Please refer the instrument manuals for the operation of the on-line analyzers.

Shutdown procedure
(1) Decelerate and unload to idle position and run for 3 minutes.
(2) Turn the ignition key to the "off" position to shut off the engine.
(3) Turn off the oil supply inlet and return valves.
(4) Shut down the dynamometer control
(5) Switch off the 24V power and main power.
(6) After 15 minutes, close the chilling water supply.
(7) Double check to make sure the testbed is completely shut down. This includes all the peripheral equipment and analyzers.