CERAMIC CATALYST SUPPORTS AND PARTICULATE FILTERS FOR DIESEL ENGINE EXHAUST AFTERTREATMENT

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Abstract. The engine exhaust aftertreatment needs for diesel heavy duty vehicles and passenger cars will be reviewed. A short discussion on current engine based emission reduction technologies will lead to the description of after treatment technologies. The predominant technologies applied are oxidation catalysts for both passenger cars as well as heavy duty trucks and busses. The oxidation catalyst utilizes a large frontal area, flow-through ceramic substrate to remove the SOF, HC, and CO emissions. High efficiency particulate matter removal can be achieved with the use of ceramic diesel particulate filters. The properties and performance data of flow-through substrates as well as particulate traps will be discussed in the paper.

1. Introduction

As emission legislation is tightening world wide, passenger car as well as truck manufacturers compliance strategy has included both, engine developments and exhaust aftertreatment measures. Especially with gasoline engines, both, the achievement in reduction of engine raw emissions and improved catalytic converter performance allowed to fulfill tight Californian LEV and ULEV and will also enable compliance with the upcoming European Stage III and IV limits.

On diesel engine powered vehicles, similar emission performances have been achieved. Flow-through oxidation catalysts in combination with advances in diesel engine technology have been the primary technology to reduce particulate mass as well as HC and CO.

With the upcoming legislation in Europe for passenger cars and discussed proposals for heavy duty vehicles (Table 1), the legislative focus now moves to the reduction of NOx as well as soot particulate matter PM.

Table 1. Mandatory and Proposed European Emission Legislation for Diesel Passenger Cars and Heavy Duty Vehicles

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC+NOx</th>
<th>NOx</th>
<th>PM</th>
<th>Diesel-Sulfur level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EU III</strong></td>
<td>0.64</td>
<td>0.56</td>
<td>0.50</td>
<td>0.050</td>
<td>350ppm</td>
</tr>
<tr>
<td><strong>EU IV</strong></td>
<td>0.50</td>
<td>0.50</td>
<td>0.25</td>
<td>0.025</td>
<td>50ppm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC</th>
<th>NOx</th>
<th>PM</th>
<th>Smoke No. 1/m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EU III</strong></td>
<td>2.1</td>
<td>0.66</td>
<td>5.0</td>
<td>0.10</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>EU IV</strong></td>
<td>1.5</td>
<td>0.46</td>
<td>3.5</td>
<td>0.02</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>EU V</strong></td>
<td>1.5</td>
<td>0.46</td>
<td>2.0</td>
<td>0.02</td>
<td>0.5</td>
</tr>
</tbody>
</table>

93
This shift in focus to NOx and PM is driven by increasing concerns on the health and environmental effect of both pollutants. In California Diesel engine exhaust being classified as a "toxic air contaminant". 

The challenge in the reduction of diesel engine emissions is characterized by:
- Lean operating conditions with Air/Fuel ratios up to 60:1
- Low exhaust gas temperatures
- High exhaust flow rates
- Varying fuel qualities (Sulfur level, Cetan Number, etc.)
- Wide range of applications (Passenger cars, Heavy Duty Trucks,..)

To successfully address this challenge, vehicle manufacturers, exhaust system manufacturers, catalyst companies and substrate and filter suppliers will have to work jointly to develop and produce reliable diesel emission reduction solutions.

2. Diesel Engine and Aftertreatment Technology Overview

The emittants to be controlled in the diesel exhaust are HC, CO, NOx and Particulate Matter (PM) including the soluble organic fraction (SOF). As mentioned earlier, both, engine technology and aftertreatment have demonstrated significant reduction of those pollutants. Evolving technologies in both areas bears significant potential for further reduction.

2.1 Engine

Diesel engine design plays a key role in achieving a balanced trade-off between
- Engine out emissions
- Noise reduction
- Torque and power output
- Fuel efficiency

The design areas critical for this trade-off are among others:

- Valve timing adjustments
- Combustion chamber design
- Fuel injection
- Exhaust gas recirculation

Fuel injection in particular has been the area where major changes occurred recently on passenger cars. Key technologies evolving in this area are fuel direct injection and increased fuel injection pressures up to 1500 bar. Increased fuel injection pressure allows for fine dispersion of the fuel in the combustion chamber resulting in improved mixture with air. Consequently, the combustion is improved enhancing fuel efficiency and reducing particulate formation. Improved distributor pump system, common rail injection and pump unit injectors are important systems to achieve injection pressures up to 2000 bar. Thus, they have significant potential for further improved engine performance and reduced engine-out emissions.
Two examples for recently introduced passenger car engines using such technology are the Audi 2.5l V6 TDI engine and the Mercedes Benz 2.2 l CDI engine. The first using a distributor pump enabling injection pressures up to 1500 bar and the latter with a common rail injection system with pressures up to 1350 bar. The potential for improved particulate emission performance as function of injection pressure is shown in Figure 1. However, it also demonstrates the increase in NOx emissions. Figure 2. Shows the emission performance of the Audi V6 2.5l TDI engine.

![Figure 1: Carbon emissions vs. NOx emissions as a function of Diesel fuel injection pressure](image)

![Figure 2: MVEG-Emission Performance of 2.5 l V6 TDI engine](image)

2.2. Diesel Emission Aftertreatment

Emission aftertreatment systems either in use or in development are:

- Oxidation catalysts
- Catalysts for simultaneous reduction of HC, CO, NOx, PM
- Lean NOx converters
- Selective catalytic reduction (SCR) using reducing agents
- Particulate filters with active regeneration
- Particulate filters with passive regeneration
Oxidation catalysts - typically on the basis of precious metals - reduces HC, CO and SOF attached to the particulates. Conversion efficiencies up to 80% for HC and CO have been observed, for PM, 50% are possible. Catalysts for the reduction of all 4 constituents additionally reduces NOx. In this case, Zeolite based adsorber components are added to the catalytic coating. NOx conversion with such systems has shown up to 20% efficiency. /5, 6/

Lean NOx converters in development have a potential for further increased conversion efficiency equal to and above of 50%. This is minimum efficiency needed for upcoming European Stage IV regulations. Such converters consist of a NOx-trap material eg. Barium, which store NOx during the lean engine operation and release and convert NOx during intermittent rich engine periods. Such systems clearly have to be well integrated into the engine management due to the required lean/rich storage and conversion strategy required. Sulfur tolerance and durability are the main areas of research and development for these concepts. /7, 8/

Selective catalytic reduction systems (SCR) are based upon V-Ti-W catalysts either coated on substrates or extruded into honeycomb structure. They require the use of a reducing agent typically NH3 formed out of an urea solution carried on board the vehicle in an extra tank. NOx reductions up to 70% have been demonstrated in passenger car and heavy duty applications. /9, 10/

Diesel Particulate Filters (DPF) are the most effective way to remove soot particulates from the exhaust gas with filtration efficiencies up to 95%. The removal of the particulates off the filter is imperative to ensure continued engine and vehicle operation at low back pressures. The onboard filter regeneration is an area of continued development. Active as well as passive techniques are under investigation and have demonstrated performance. /11, 12, 13/

1. Active
   - Fuel burner
   - Electrical heating

2. Passive
   - Catalytic coatings on the filter
   - Catalytic fuel additives
   - Continuously regenerating trap (CRT)

Ceramic cordierite substrates and particulate filters are the predominant and key materials used with and developed for these aftertreatment technologies. The requirements and properties of these substrate and filter materials are described in the next paragraph.

3. Filter and Substrate Properties

3.1. Materials and Filter Design

The most widely used ceramic wall-flow filter is extruded from synthetic cordierite, with chemical formula 2MgO•2Al2O3•5SiO2. Cordierite offers unique properties which include high porosity, low thermal expansion, high thermal shock resistance, and a tailorable microstructure, to meet filtration and back pressure requirements set by engine manufacturers. /14/
Figure 3 is a schematic of the diesel particulate filter with checkerboard plug pattern. The filter has a honeycomb configuration with individual channels open and plugged at opposite ends. The material used to plug the cell openings is similar to the body in composition and during firing seals to the cell walls. The plugged cells are impervious to gas flow. /14/

Fig. 3. Checkerboard Plug pattern of DPF

The diesel exhaust gases enter the open end, flow through the pores in the cell walls, and exit through the adjacent channel, Figure 4. Soot particles too large to flow through the pores become trapped on the cell walls and begin build up of a layer that acts as a membrane. With increasing thickness of the soot layer, the hydraulic diameter of the channels decreases, resulting in higher back pressure. At this point the filter has to be regenerated to remove soot and lower the back pressure to acceptable limits. The soot is oxidized to CO₂ during the regeneration process to clean the filter. /14, 15/

Fig. 4. Exhaust Flow Passage through Wall Flow Filter

Design consideration of the filters include geometric properties to meet performance requirements. The filters are designed with high geometric surface area and large open frontal area that have impact on filter efficiency and pressure drop. This is achieved through the extrusion process and die technology.

In addition, low thermal mass and heat capacity, high use temperature, coatability, washcoat compatibility, strength and oxidation resistance are factors to consider for achieving maximum performance.
3.2. Cell Configuration and Properties

Figure 5 shows the wall-flow filter with square cell geometry. A number of terms have used to describe geometric and hydraulic properties of cellular substrates. These properties can be defined in terms of repeat distance or cell spacing L, and wall thickness, t. /14/

The cell density N is defined as the number of cells per unit of cross-sectional area and is expressed in units of cells per square inch (cpsi).

\[ N = \frac{1}{L^2} \]  

(1)

The open frontal area (OFA) and specific filtration area (SFA)

\[ OFA = 0.5 (L - t/L)^2 \]  

(2)

are defined in Equations 2 and 3 as a function of wall thickness and cell spacing. The specific surface area (SFA) is directly proportional to the cell density defined in equation 1

\[ SFA = \frac{2(L - t)}{L^2} \]  

(3)

Fig. 5. Wall Flow Filter with Square Cell Geometry

The hydraulic diameter defined by Equation 4, decreases as the cell density increases. The \( D_h \) is different for uncoated and coated substrates.

\[ D_h = L - t \]  

(4)

Coating with catalyst changes the wall thickness. Therefore a portion of the total pressure drop due to gas flow through the channels depend inversely on the square of the hydraulic diameter increase. Hence, care must be used in selection of the appropriate cell density.

Filtration capacity is another key parameter used for designing filter efficiency. It is defined as the total soot that can be collected prior to regeneration and is related directly to the total filtration area, TFA.

\[ TFA = 2(L-t)/L^2 \cdot V_f \]  

(5)

Where the filter volume \( V_f \) is given by Equation 7 in which \( d \) and \( l \) denote filter diameter and length, respectively.

\[ V_f = \frac{\pi}{4d^2l} \]  

(7)
3.3. Physical Properties and Performance

Physical properties of ceramic cordierite filters can be tailored to meet different filtration efficiency and pressure drop set by engine manufacturers. The physical properties can be controlled by managing, microstructure (porosity, pore size distribution and microcracking), coefficient of thermal expansion, strength (crush), isostatic strength and modulus of rupture, E-Modulus (structural), and fatigue behavior. /14/

Changes in the microstructure affects not only CTE, but strength, thermal shock resistance, microcracking, modulus, filter washcoat and catalyst interactions. The microstructure is controlled by selection of ceramic composition and manufacturing process.

Table 3 summarizes porosity, pore size distribution and geometric surface area of four DPFs. The EX-80 filter is the industry standard while the EX-47, EX-54 and EX-66 are earlier products, which are not in production anymore. They are listed here as reference only. The filters were designed for different filtration efficiency and back pressure specifications. EX-80 and EX-47 with small mean pore diameter were designed for high filtration (>90%). The EX-54 and EX-66 with larger pore size have lower back pressure and filtration efficiency (60-75%). However, there is a trade-off, as the pressure drop decreases with increasing pore size, so does the filtration efficiency.

The todays EX-80 composition has been demonstrated to combine high filtration efficiency and low pressure drop. /14, 15/

The wall porosity also affect mechanical strength. As the wall porosity increases the mechanical strength decreases, thus calling for a compromise in selecting the wall porosity. Most filters are designed to yield a wall porosity of 48-50%. The EX-66 wall thickness is 0.025 inches and the others 0.017 inches.

In Table 5 the MOR and MOE denote modulus of rupture and modulus of elasticity, respectively. The axial and tangential modulus are key parameters that impact the filters thermal durability. Thermal durability refers to the filter’s ability to withstand both axial and radial temperature gradients during regeneration. The filters all have high modulus values at elevated temperatures, which is a requirement for long term durability. /14/. The low E-modulus data for the filters indicate that the filters are similar in stiffness compared to EX-66. The substrates high crush and isostatic strength for mechanical durability, see Table 4.

Table 3. Porosity, Open Frontal Area and Filtration Area of Cordierite (100 cpsi) /14,15/

<table>
<thead>
<tr>
<th>DPF</th>
<th>Porosity</th>
<th>Mean pore size (μm)</th>
<th>OFA</th>
<th>Filtration Area (m²/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX-47</td>
<td>50%</td>
<td>13.4</td>
<td>34.4%</td>
<td>16.6</td>
</tr>
<tr>
<td>EX-54</td>
<td>50%</td>
<td>24.4</td>
<td>34.4%</td>
<td>16.6</td>
</tr>
<tr>
<td>EX-66</td>
<td>50%</td>
<td>34.1</td>
<td>34.4%</td>
<td>16.6</td>
</tr>
<tr>
<td>EX-80</td>
<td>48%</td>
<td>13.4</td>
<td>34.4%</td>
<td>16.6</td>
</tr>
</tbody>
</table>

The axial CTE for the filters is the average value over the range 25-800°C. The low CTE ensures low thermal stresses and excellent durability needed for multiple regenerations. Of the four filters shown in Table 4, EX-80 has the lowest CTE over the entire range which implies lower thermal stresses and excellent durability.
Table 4. Crush and Isostrength Data for DPF /14/:

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EX-47</td>
<td>1130</td>
<td>380</td>
<td>585</td>
<td>500</td>
<td>0.39</td>
</tr>
<tr>
<td>EX-54</td>
<td>900</td>
<td>300</td>
<td>460</td>
<td>390</td>
<td>0.45</td>
</tr>
<tr>
<td>EX-66</td>
<td>1300</td>
<td>430</td>
<td>660</td>
<td>560</td>
<td>0.54</td>
</tr>
<tr>
<td>EX-80</td>
<td>1595</td>
<td>325</td>
<td>500</td>
<td>425</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 5. Modulus (RT) and Thermal Expansion of Cordierite DPF /14,15/:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EX-47</td>
<td>365</td>
<td>142</td>
<td>0.81</td>
<td>8.8</td>
</tr>
<tr>
<td>EX-54</td>
<td>320</td>
<td>131</td>
<td>0.83</td>
<td>8.7</td>
</tr>
<tr>
<td>EX-66</td>
<td>418</td>
<td>176</td>
<td>1.06</td>
<td>10.5</td>
</tr>
<tr>
<td>EX-80</td>
<td>410</td>
<td>184</td>
<td>0.75</td>
<td>3.3</td>
</tr>
</tbody>
</table>

The filters are designed to deliver consistent, reliable and durable performance under the demanding conditions of everyday operation. Thus design targets to meet performance standards include high geometric surface area and large open frontal area for adequate filtration, and high thermal shock resistance to impact soot regeneration, and high porosity to minimize pressure drop.

The filter cell walls contain a series of interconnected pores of a volume and size sufficient to enable the diesel exhaust gas to flow completely through but retain most of the particles. The soot is trapped in the filter walls when it begins to build up on the surface of open pores to from a membrane. With increasing thickness of the soot layers, the hydraulic diameter of the channels decreases, resulting in higher back pressure. At this point the filter has to be regenerated to remove soot and lower the back pressure.

Each of the design targets mentioned above can be managed to improve overall filter efficiency. The microstructure and plugging pattern can be altered to obtain filtration efficiencies ranging from 50% to 95%. Consequently, changes in porosity, volume, pore size distribution and wall thickness affect soot collection efficiency.

3.4. Particle Size Distribution

Diesel engines emit particulate matter (PM), a complex mixture of organic and inorganic compounds, gas, liquid and solid phase materials. The particulate matter is divided into three fractions: a solid fraction, mostly elemental carbon; soluble organic fraction (SOF) derived from fuel and lubricating oil; and sulfate particulates (SO₄). The sum of these three fractions is defined as the total particulate matter (TPM). The solid particulate fraction is composed of carbon spherules formed in the combustion chamber. Some particles may agglomerate and adsorb hydrocarbons or other species on their surfaces. The solid fraction particles are a mixture of nuclei mode and accumulation mode particles. The nuclei mode particle size diameter range from 10 to 80 nm. The accumulation mode particles are formed by agglomeration of nuclei particles with diameters between 80 and 1000 nm. About 90% of diesel particulates are within these two ranges, comprising a bimodal size distribution. /12-18/
The smaller particulates have generated health concerns due to their potential link to adverse respiratory ailments. New diesel engines nearly meet standards for particulate matter (measured by mass), but still emit fine particles (measured by physical size and number). Health considerations may lead to future regulation of fine particle emissions, such as PM$_{2.5}$ standards under discussion in the U.S. and Europe. /1, 19/

Health concerns have generated an increased interest in diesel particulate size distribution and removal. Ceramic diesel particulate filters have been confirmed worldwide as effective for trapping soot particles. Several studies have been conducted with focus on removal of fine particulates from diesel exhaust. A particle size distribution study was conducted at FEV systems laboratory to determine whether EX-80 was effective in reducing the fine particles. The FEV data clearly demonstrates that particulate filters reduces the number of particles emitted at the tailpipe by more than two orders magnitude, while virtually eliminating particles larger that 35 mm. The data also describes the influence of DPFs on particle size distribution under severe engine loads. /12, 13/

The tests were performed on a turbocharged heavy-duty (HSD) 6.9L MAN diesel engine calibrated for Euro 2 exhaust regulations. The engine was mounted on a steady-state test bench. Engine specifications are shown in Table 6. The engine was equipped with an EX-80 DPF. A description of the EX-80 specifications is shown in Table 7. The tests were conducted at four operating points listed in Table 8. /12, 13/

**Table 6. 6.9L MAN Engine /12, 13/**

<table>
<thead>
<tr>
<th>Combustion System</th>
<th>Direct injection / turbo-charged / intercooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>cylinder / arrangement</td>
<td>6 / in-line</td>
</tr>
<tr>
<td>displacement</td>
<td>6.871 cm³</td>
</tr>
<tr>
<td>compression Ratio</td>
<td>16,5 : 1</td>
</tr>
<tr>
<td>max. power</td>
<td>169kW</td>
</tr>
<tr>
<td>@ rated speed</td>
<td>2,400 min⁻¹</td>
</tr>
<tr>
<td>max. torque</td>
<td>860 Nm</td>
</tr>
<tr>
<td>@ intermediate speed</td>
<td>1,440 min⁻¹</td>
</tr>
<tr>
<td>max. BMEP</td>
<td>15,5 bar</td>
</tr>
<tr>
<td>min. BSFC</td>
<td>198 g/kWh</td>
</tr>
<tr>
<td>calibrated for exhaust reg.</td>
<td>EURO II</td>
</tr>
</tbody>
</table>

1) Acc. Manufacturer’s information

**Table 7. EX-80 Filter Specification /12, 13/**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>10.5” x 12.0”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>17 liters</td>
</tr>
<tr>
<td>Cell density</td>
<td>100 cpsi</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>17 mil</td>
</tr>
<tr>
<td>Material</td>
<td>EX-80</td>
</tr>
<tr>
<td>Total Porosity</td>
<td>48%</td>
</tr>
<tr>
<td>Mean Pore Size</td>
<td>13 microns</td>
</tr>
</tbody>
</table>

Two types of diesel fuel was used Swedish Class 1 diesel fuel with sulfur (10 ppm) and a European standard fuel quality with 350 ppm.
Two different particle sizing techniques were used, sedimentation/inertial and electrical mobility. Detail description of the techniques will not be discussed and can be found in reference. Sedimentation/inertial technique measures mass inertial of the particles entering the impactor. The impactor provides mass distribution per class size in which particle number per class can be calculated. The number weighted size particle distribution was determined with a Differential particle Mobility Size. This consisted of a combination of a Differential Mobility Analyzer followed by a Condensation Nucleus Counter.

Figure 8 shows the particles size distribution measured with and without DPF at 1400 rpm, full load with standard fuel quality 350 ppm. The number of particle decreases by almost three powers. /12, 13/

| Operating Points | Engine Speed [rpm] | Load | $\eta_{\text{Total Particulates}}$ | $\eta_{\text{Lead}}$ | $\eta_{\text{SOF}}$ | $\eta_{\text{Sulfate}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600</td>
<td>idle</td>
<td>97%</td>
<td>99%</td>
<td>97%</td>
<td>71%</td>
</tr>
<tr>
<td>2</td>
<td>1440</td>
<td>25%</td>
<td>95%</td>
<td>99%</td>
<td>80%</td>
<td>85%</td>
</tr>
<tr>
<td>3</td>
<td>1440</td>
<td>100%</td>
<td>98%</td>
<td>99%</td>
<td>84%</td>
<td>83%</td>
</tr>
<tr>
<td>4</td>
<td>2400</td>
<td>100%</td>
<td>94%</td>
<td>99%</td>
<td>49%</td>
<td>75%</td>
</tr>
</tbody>
</table>

The efficiency of the DPF on particulates is shown in Table 8. The total particulate mass was reduced by more than 94% at all operating points. /12/ The fuel used was the standard fuel quality with 350 ppm.

The diesel particulate filter is very efficient at removal of fine particles. As the number of small particles increase with new diesel engines and health concerns are justified, PM emissions regulation may have to change. This may include the total mass of particulates and their size and number. /12/

4. Application Experience

These technologies utilizing ceramic components are applied to on-highway, off- highway and stationary applications. On-highway applications make use of the oxidation catalyst to reduce PM on European passenger cars, North American Light & Medium duty trucks, and Worldwide Urban Bus retrofit. Additionally, many urban buses employ particulate filters for PM reduction.

Off-highway applications utilize both oxidation catalysts and particulate filters to reduce PM on mining vehicles and construction vehicles that operate in enclosed areas.

Stationary applications include power generation for primary, backup, and marine utility power and can require an oxidation catalyst or particulate filter to reduce PM, or selective catalytic reduction (SCR) for conversion of oxides of nitrogen (NOx).
On-highway Experience

Millions of diesel fueled passenger cars in Europe have utilized oxidation catalysts since 1989 to reduce the soluble organic fraction particulate (SOF), hydrocarbons (HC), and carbon monoxide (CO) emissions. This technology has enjoyed very positive field experience without an oxidation catalyst recall. The oxidation catalyst is integrated into the engine management and emissions control strategies of the engine and vehicle. Furthermore, consumer acceptance equals that of the three way catalytic converter used on gasoline fueled vehicles. The key issue with the oxidation catalyst is the lack of direct NOx reduction. In addition to passenger cars in Europe, since 1993 over 1 million trucks and buses in North America are using oxidation catalysts to realize similar benefits as well as odor and smoke reduction. The primary applications have been on OEM light/medium duty trucks with 6 – 9 liter engines. Again the field experience has been positive. The number of failures in the field is extremely low, the fuel consumption penalty has been slight, and the systems have met the extended durability requirements of trucks and buses. The key issues with the oxidation catalysts in these applications include the lack of direct NOx reduction and also fouling and plugging in extreme cold climates and certain light driving cycles.

Urban buses around the world have been involved in retrofit programs since the 1980’s. Major programs have been initiated in New York City, Athens, London, Seoul, and cities in Sweden. Historically, most utilized particulate filters with auxiliary regeneration systems. Most of them also had durability and reliability problems in addition to very high costs. More recently bus retrofit programs in the United States are using oxidation catalysts. Buses in London and the Swedish Environmental Zones are utilizing the continuously regenerating trap, a system that employs both a catalyst and a particulate filter. In the meanwhile approximately 9000 of such continuously regenerating systems are on the road and performing to expectation /20/.

Off-highway Experience

Off-highway applications of aftertreatment include over 100,000 systems around the world for use in enclosed environments to address CO and PM reduction. Mining vehicles, construction vehicles and fork lift trucks employ oxidation catalysts and particulate filters. Some of these filter systems may be regenerated off line during an off shift or during maintenance in addition to the more traditional regeneration techniques mentioned earlier.

Stationary systems with very large diesel engines for primary power generation may require SCR technology to reduce NOx in urban centers. Engines on smaller generator sets for backup or auxiliary power will use particulate filters and in some cases oxidation catalysts.

4.3. System Lay-out & Performance

4.3.1. Oxidation Catalyst

The sketch in Figure 6. shows a typical converter muffler containing both the oxidation catalyst and muffler in one package. The oxidation catalyst is made up of the ceramic substrate, washcoat/catalytic coating, intumescent mat material which is enclosed in a stainless steel
can. The ceramic substrates currently used in US trucks and European passenger cars are monoliths containing between 200 – 400 cells per square inch of frontal area. The catalyst volume is usually equal to the displacement volume of the engine. Proper packaging in the stainless steel can and intumescent mat provides the mechanical integrity and vibration resistance necessary to meet the durability requirements on both passenger cars and heavy-duty trucks and buses.

![Exhaust System Diagram](image)

Fig. 6. Oxidation Catalyst/Muffler Combination

The modern diesel oxidation catalyst is designed to primarily reduce particulate emissions. However, the oxidation catalyst will oxidize the CO and HC, as well as the liquid hydrocarbons adsorbed onto the carbon particles. Total particulate mass is reduced 40% – 50%, with SOF being reduced by as much as 90%. HC and CO emissions can realize an 80% conversion rate and the noxious odor of the exhaust can be virtually eliminated. White smoke emissions caused by raw fuel in the exhaust during cold starts can be reduced in older engines cutting opacity by 50% - 70%.

4.3.2. Particulate Filter

The Figure 7 schematically shows a canned ceramic particulate filter with catalysed walls. The packaging system is similar to the ceramic oxidation catalyst utilizing an intumescent mat material stainless steel can.

![Particulate Filter Diagram](image)

Fig. 7. Catalyzed Particulate Filter
The wall flow DPFs filtration efficiency is above 90% as mentioned earlier. Recent measurements on a 6.9L HD engine /13/ demonstrated this efficiency (Figure 8). Also, the ceramic particulate filter reduced particulate mass but particle number reduction as well across the entire particle size range down to approximately 15 nanometer.

![Graph showing particle size distribution with and without Wall Flow trap](image)

*Fig. 8. Particle Size distribution with and without Wall Flow trap /13/*

Regeneration of the filter can be accomplished with either passive or active approaches. Passive techniques include fuel additives and catalyst coatings, which cause regeneration in a continuous or periodic manner during the regular duty cycle of the engine. Catalyst coatings and fuel additives enable the oxidation of the carbon soot to occur at lower temperatures (~375 Degrees C) than would normally occur unaided (~500 Degrees C). Active approaches include auxiliary heat sources such as electric heaters or fuel burners. These systems will periodically raise the temperature of the carbon soot to the oxidation point. Active regeneration systems are much more complex than passive systems. They require sophisticated mechanical and electrical hardware including controls to manage the regeneration process.

Another passive technique for regeneration of the filter is the continuously regenerating trap shown in Figure 9.

![Continuously Regenerating Trap CRT® (JM)](image)

*Fig. 9. Continuously Regenerating Trap CRT® (JM) /12/*
This device employs both a catalyst component and a filter. Both components are packaged together in the same can with the catalyst upstream and the filter downstream. The catalyst produces nitrogen dioxide, which then reduces the oxidation temperature of the soot trapped in the downstream filter. To be successful this device requires extremely low sulfur content fuel, < 50ppm. Passive regeneration techniques for filters are clearly more desirable due to their simplicity.

5. Summary and Conclusion

For engine and vehicle manufacturer to meet the 2004/2005/2008 emissions standards, developments in both engine technology and aftertreatment are required. Exhaust aftertreatment will help to resolve the NOx-PM trade-off. The challenge of NOx reduction in lean diesel exhaust gas will have to be addressed, as well as efficient particulate removal. Cordierite ceramic substrates and particulate filters have played a significant role to help solve this challenge and will continue to do so.

This development will be based upon the solid history of the diesel exhaust oxidation catalyst, which -supported by the ceramic substrate- is in wide use throughout the world in multiple applications. With a proven track record for HC, CO and particulate reduction for passenger cars and heavy duty vehicles.

Ceramic wall flow particulate filter technology continues to evolve and is the only known technology to be 95%+ effective on the entire particle size distribution for diesel exhaust. Engineering continues on materials to improve durability and on regeneration systems to improve reliability and reduce cost.

New DPF materials are in development and will emerge to the market. DPF design tools are being developed as well to support DPF system design for passenger car to heavy duty truck applications.

A combination of these technologies and engine technologies will be required to meet the emissions standards of the future.

4. References


