Diesel Particulate Filters

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In-Depth Papers

- Diesel Filter Regeneration

Abstract: Diesel particulate filters capture particle emissions through a combination of surface-type and deep-bed filtration mechanisms, such as diffusional deposition, inertial deposition, or flow-line interception. Collected particulates are removed from the filter, continuously or periodically, through thermal regeneration. Diesel filters are very effective in controlling the solid part of PM emission, but maybe ineffective in controlling non-solid particulate fractions. Filters have been commercialized for selected retrofit applications and are on the verge of commercialization for highway light- and heavy-duty diesel engines.

Introduction

Diesel particulate traps are devices that physically capture diesel particulates to prevent their release to the atmosphere. Some of diesel filter materials which have been developed show quite impressive filtration efficiencies, frequently in excess of 90%, as well as acceptable mechanical and thermal durability. In fact, diesel traps are the most effective control technology for the reduction of particulate emissions with high efficiencies. More precisely, due to the particle deposition mechanisms utilized in these devices, traps are effective in controlling the solid fraction of diesel particulates, including elemental carbon (soot) and the related black smoke emission. It must be remembered that traps may have limited effectiveness, or be totally ineffective, in controlling the non-solid fractions of PM, such as the SOF or sulfate particulates. For this reason, trap systems designed to control the total PM emission are likely to incorporate additional functional components targeting the SOF emission (e.g., oxidation catalysts) and sulfate particulates (e.g., ultra low sulfur fuels).

All diesel particulate traps of practical importance are *diesel particulate filters* (DPF). There are several particle deposition mechanisms other than filtration, which are commonly employed in industrial dust separation equipment. These mechanisms include gravity settling, centrifugal separation, and electrostatic trapping. Gravity settling and centrifugal separation (cyclones) are ineffective in capturing of diesel particulates due to their small, sub-micron size and low density. Diesel aerosol tends to behave in cyclones like gas rather than a gas-solids mixture. A combination of electrostatic coagulation of fine diesel particles (upstream) with a cyclone (downstream) can theoretically increase the recovery efficiency. The electrostatic traps, however, appear to be impractical for diesel engine application.

Even though the term “trap” covers a wider range of devices, it is often used as a synonym for “diesel filter”. Such use of the term “diesel trap” in reference to filter devices was more common in older literature. In the recent years, there is a trend to replace it with the more precise term “diesel particulate filter”.

Due to the low bulk density of diesel particulates, which is typically below 0.1 g/cm^3 (the density depends on the degree of compactness; as an example, a number of 0.056 g/cm^3 was reported by Wade [Wade 1981]), diesel particulate filters can quickly accumulate considerable volumes of soot. Several liters of soot per day may be collected from a heavy-duty truck or bus engine. The collected particulates would eventually cause excessively high exhaust gas pressure drop in the filter, which would negatively affect the engine operation. Therefore, diesel filter systems have to provide a way of removing particulates from the filter to restore its soot collection capacity. This removal of particulates, known as the filter *regeneration*, can be performed either continuously, during regular operation of the filter, or periodically, after a pre-determined quantity of soot has been accumulated. In either case, the regeneration of filter systems should be “invisible” to the vehicle driver/operator and should be performed without his intervention. In most cases, thermal regeneration of diesel filters is employed, where the collected particulates are removed from the trap by oxidation to gaseous products, primarily to carbon dioxide (CO_2). The thermal regeneration, schematically represented in Figure 1, is undoubtedly the cleanest and most attractive method of operating diesel filters.

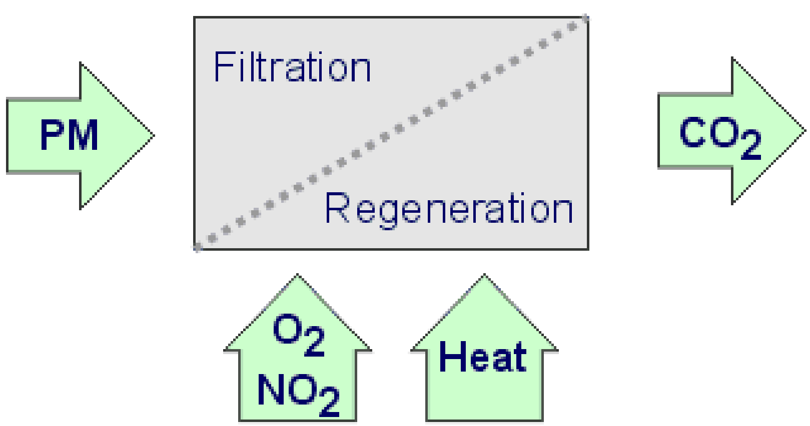

Figure 1. Schematic of Particulate Filter with Thermal Regeneration

To ensure that particulates are oxidized at a sufficient rate, the filter must operate at a sufficient temperature and oxidizing gases, such as oxygen or nitrogen dioxide (or its precursors), must be supplied to the filter. In some filter systems, the source of heat (as well as of the oxidizing gases) is the exhaust gas stream itself. In this case, referred to as the *passive filter*, the filter regenerates continuously during the regular operation of the engine. Passive filters usually incorporate some form of a catalyst, which lowers the soot oxidation temperature to a level that can be reached by exhaust gases during the operation of the vehicle. Another approach which may be needed to facilitate reliable regeneration involves a number of active strategies of increasing the filter temperature (engine management, electric heaters, ...). Regeneration of such systems, known as *active filters*, is usually performed periodically, as determined by the vehicle's control system. The classification of particulate filter systems is presented in more detail in Diesel Filter Systems.

An alternative strategy involves the use of disposable filter cartridges, which are replaced with new units once filled with soot. Particulate traps of this kind are used in some occupational health environments. Such maintenance intensive filter systems are clearly not acceptable in mobile, highway vehicle applications.

Principle of Operation

Filter Configuration

The most common design of diesel particulate filter is the *wall-flow monolith*. It is an extruded, usually cylindrical ceramic structure with many small, parallel channels running in the axial direction. Those familiar with catalyst technologies realize that this description, so far, matches that of the catalytic converter substrate. Indeed, the design of diesel filter monoliths has been derived from automotive, “flow-through” catalyst substrates. There are, however, two important differences between these structures: (1) the wall-flow monoliths are made of ceramics of higher and more precisely controlled porosity, and (2) adjacent channels in the wall-flow filters are alternatively plugged at each end, thus forcing the gas to flow through the porous walls which act as a filter medium. The flow pattern difference between the flow-through and the wall-flow substrate is illustrated in Figure 2.

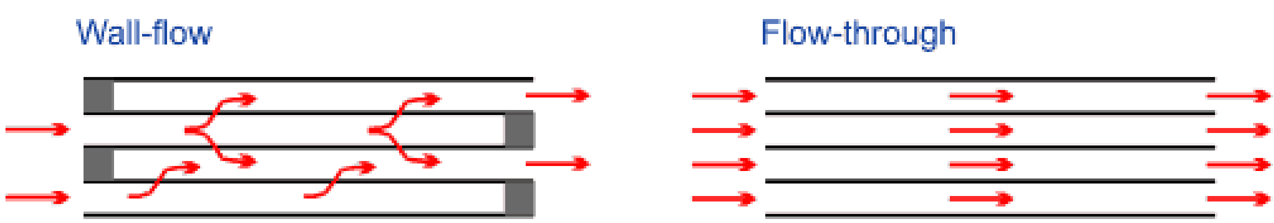

Figure 2. Wall-Flow and Flow-Through Substrates: Flow Pattern

The wall-flow filter substrates are easily distinguished from catalyst substrates by the characteristic checkerboard pattern created by the open and plugged cells at their inlet (as well as outlet) face, Figure 3.

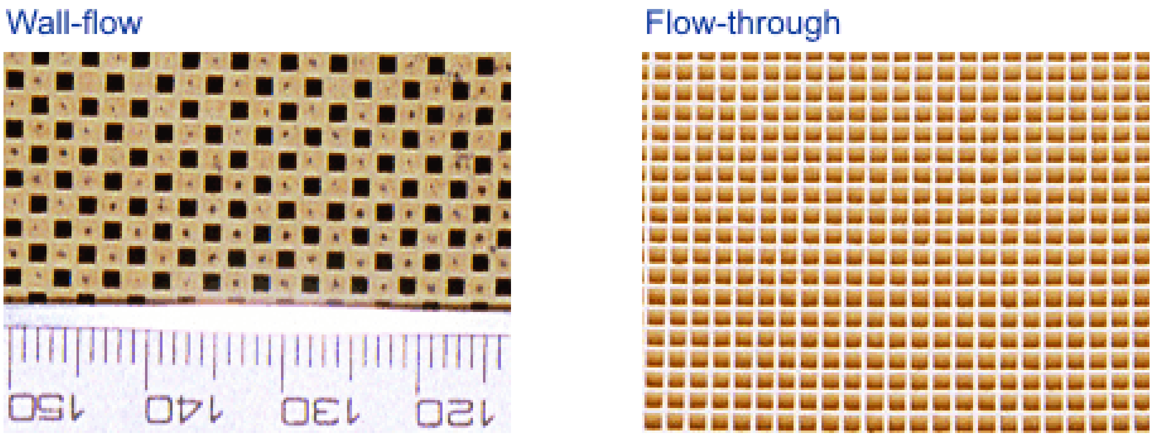

Figure 3. Wall-Flow and Flow-Through Substrates: Inlet Cell Pattern

A number of other, alternative filter designs and materials have been developed. Examples include cartridges made of ceramic fibers, various types of foams, or sintered metal structures. An overview of these technologies is presented in the Diesel Filter Materials paper.

Regardless of the type of material or design, the filter media is ultimately packaged into steel container which is installed in the exhaust system of the vehicle. The DPF can be packaged as a stand-alone unit resembling a catalytic converter but usually of bigger size. In an alternative design, the DPF is placed inside a muffler. However, due to the good noise attenuation properties of many filter media, the filter unit can frequently replace the muffler without any additional provisions for noise attenuation. An example design of a diesel particulate filter is shown in Figure 4.

Figure 4. Cutout of Catalyzed DPF for Urban Bus and Nonroad Applications

(Courtesy of Nett Technologies)

Filtration Mechanisms

The particulate collection by any type of diesel filter is based on separation of the gas-borne particles from the gas stream by deposition on a collecting surface. This separation involves passage of the gas through a porous barrier which retains the particulates. Filters, depending on the type of the barrier, may be divided into (1) deep-bed filters and (2) surface-type filters. In the deep-bed filters, the mean pore size of filter media is bigger than the mean diameter of collected particles. The particles are deposited on the media through a combination of depth filtration mechanisms which are driven by various force fields. As an example, the force fields may be related to velocity or concentration gradients in the gas. In the surface-type filters the pore diameter is less than the particle diameter. The particles are deposited on the media through sieving. These two types of filtration are shown in Figure 5.

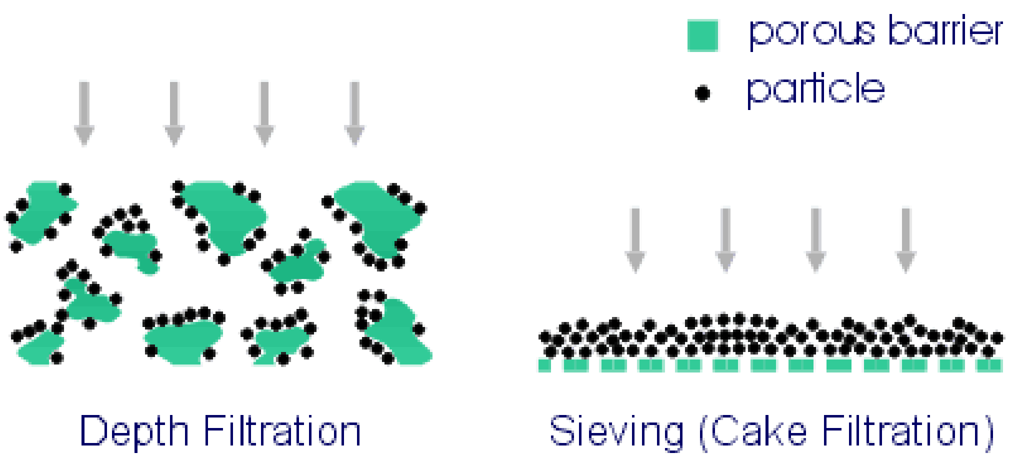

Figure 5. Types of Filtration

Depth filtration is the main filtration mechanism in most dust collection devices, as well as in majority of diesel filters. For example, engine intake-air cleaners work predominantly through the depth filtration.

The layer of collected dust, or diesel particulates, is itself the principal filter medium in the surface-type filters. That layer is commonly referred to as “filtration cake” and the process is called “cake filtration”. Cake filtration is very common in liquid filtration. Pure cake filtration is not observed in diesel filters or, generally, in dust collecting filters. However, some diesel filters, such as ceramic wall-flow monoliths, may work through a combination of depth and surface filtration. A filtration cake develops at higher soot loads, when the depth filtration capacity is saturated and a particulate layer starts covering the filtration surface. A visible filtration cake would also eventually develop at the pleated surface of an engine intake-air cleaner (in that case, however, it would indicate that the air cleaner service has been long overdue).

The depth filtration relies on three mechanisms of aerosol deposition [Perry 1984]:

- Diffusional deposition
- Inertial deposition
- Flow-line interception.

These mechanisms are illustrated in Figure 6, 7 and 8. The large circle in the middle represents a collecting body in the filter media, say a fiber in a ceramic fiber filter. Diesel exhaust gas flows around the filter media, as indicated by the streamlines. The small black-red spheres represent diesel exhaust particles traveling with the gas stream.

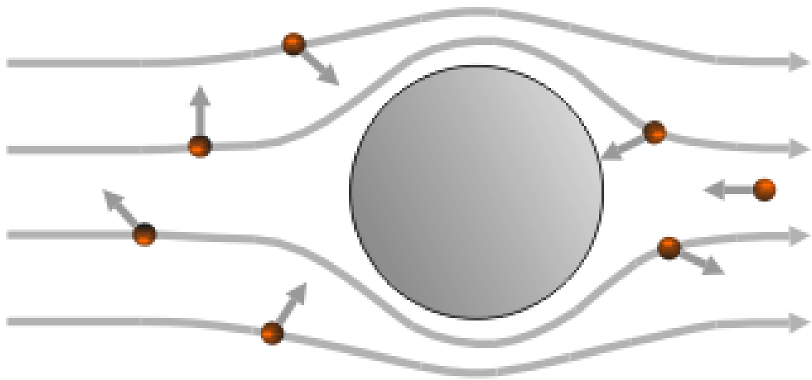

Figure 6. Diffusional Deposition

Diffusional deposition (Figure 6) depends on the Brownian movement exhibited by smaller particulates, particularly those below 0.3 µm in diameter. Those particulates do not move uniformly along the gas streamlines. Rather, they diffuse from the gas to the surface of the collecting body and are collected.

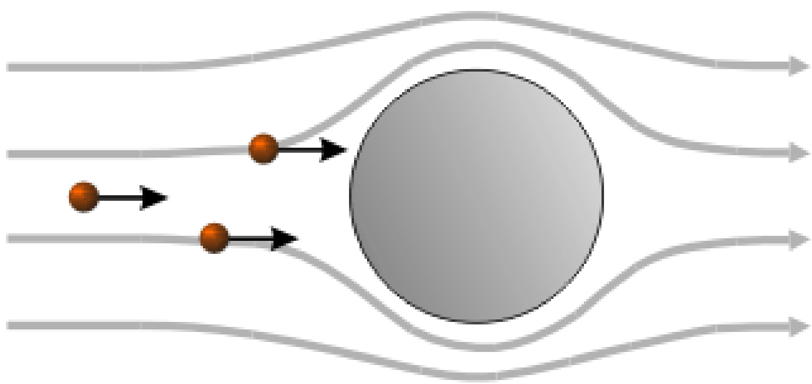

Figure 7. Inertial Deposition

Inertial deposition (Figure 7), also called inertial interception, becomes more important with increasing particle size (mass). On approaching the collecting body, particles carried along by the gas stream tend to follow the stream but may strike the obstruction because of their inertia.

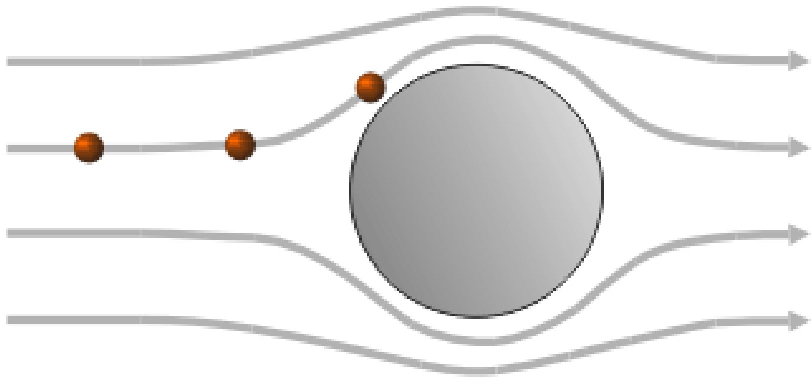

Figure 8. Flow-line Interception

Flow-line interception may occur when a fluid streamline passes within one particle radius of the collecting body. Then, a particle traveling along the streamline will touch the body and may be collected without the influence of Brownian diffusion or inertia.

Performance of diesel particulate filters may be expressed as the *filtration efficiency* (E) or *penetration* (1-E). The filtration efficiency is the mass ratio of the particulate matter collected on the filter to the particulate matter entering the filter. The penetration is the mass ratio of the particulates escaping to the particulates entering the filter. Both filtration efficiency and penetration may be expressed as percentages.

The depth filtration is characterized by somewhat lower filtration efficiency and lower pressure drop than the cake filtration. Particulates which were already deposited on a deep-bed filter may be also re-entrained by the gas causing a decrease in the observed filtration efficiency. That phenomenon is termed “blow-off” of the collected particulate matter. Blow-offs occur at high exhaust gas flow rates or at rapid flow accelerations.

The cake filtration is characterized by higher filtration efficiency and relatively high pressure drop. The pressure drop steadily increases with the increase of filtration cake thickness.

Regeneration

All filter materials are designed to hold a certain quantity of soot. If the filter becomes overloaded, the particulates create an obstruction to the gas flow, which manifests itself in increased pressure drop and may lead to clogging of the filter. Therefore, the filter system has to provide reliable regeneration mechanisms to ensure problem free operation. The soot holding capacity in most filter systems is sufficient only for some hours or, at most, a few of days of engine operation. Some DPF systems regenerate continuously. Others, which regenerate periodically, must perform this operation fairly frequently, usually at least once per day.

See **Diesel Filter Regeneration** for more information.

The exhaust gas and/or filter temperature is the most important parameter influencing filter regeneration. Oxidation of carbon particulates can be considered a kinetic process, the rate of which can be described by the laws of chemical reaction kinetics. Again, certain analogies can be drawn between the oxidation of gases in the catalytic converter and the oxidation of soot in diesel filters, especially those which operate in the continuous regeneration regime. Filters do provide longer residence times (relative to catalytic converters), which are required to oxidize the large size particles (relative to gas molecules). Similar to gases, the soot oxidation rates increase at higher temperatures and decrease, possibly slowing down to zero, at low temperatures. Contrary to the catalytic converter, however, material which is not oxidized, cannot be released from the filter. Instead, unoxidized particles are accumulated until conditions change (e.g., as a result of increased temperature) and oxidation rates increase. It is an important function of the filter system to provide mechanisms which prevent accumulation of soot that would exceed the filter holding capacity.

Failures of filter systems usually result in more serious consequences to the vehicle driver than failures of catalytic converters. A deactivated catalyst in the converter results in excessive emissions, but in most cases does not create adverse effects to the engine or vehicle. On the other hand, a diesel particulate filter that fails to regenerate is likely to become clogged, effectively stalling the engine and immobilizing the vehicle.

Particulate filters also capture inorganic ash particles contained in the PM emission. These incombustible particles cannot be removed from the filter through thermal regeneration. Even though the contribution of ashes in the total PM is much less than inorganic carbon, the accumulation of ash causes a gradual increase in the pressure drop in the filter over its lifespan. Filters can be cleaned from ashes only through dedicated maintenance procedures, such as washing with water or reversing the direction of flow through the filter. The frequency of cleaning is typically not more than once per year.

DPF Performance

Particle Mass

Due to the physical particle collection mechanisms, as discussed above, filters are effective in collecting the solid fraction of diesel particulate matter, including inorganic carbon and ash. The effectiveness of diesel filters in controlling the organic fraction of DPM (SOF) depends on the type of filter and on its operating conditions. Furthermore, diesel particulate filters are not only ineffective in controlling sulfate particulates, but, in the case of catalytic filters, may significantly increase this emission through catalytic oxidation of sulfur dioxide.

The impact of particulate filters on PM composition is illustrated in Figure 9 [Andersson 2001]. The filter, a two-stage system incorporating an oxidation catalyst and a wall-flow DPF, was installed on an Euro 1 engine and tested on the R-49 schedule, which is dominated by the full speed - full load mode, resulting in high average exhaust gas temperature. It is clear from the graph that the DPF is extremely effective in removing elemental carbon particulates (black, bottom portion of each bar). SOF fractions from fuel and oil are somewhat reduced by the catalyst portion of the filter system. Despite the use of ultra low sulfur fuels, sulfate particulates are increased (especially so in the test with UKULSD fuel of higher sulfur content).

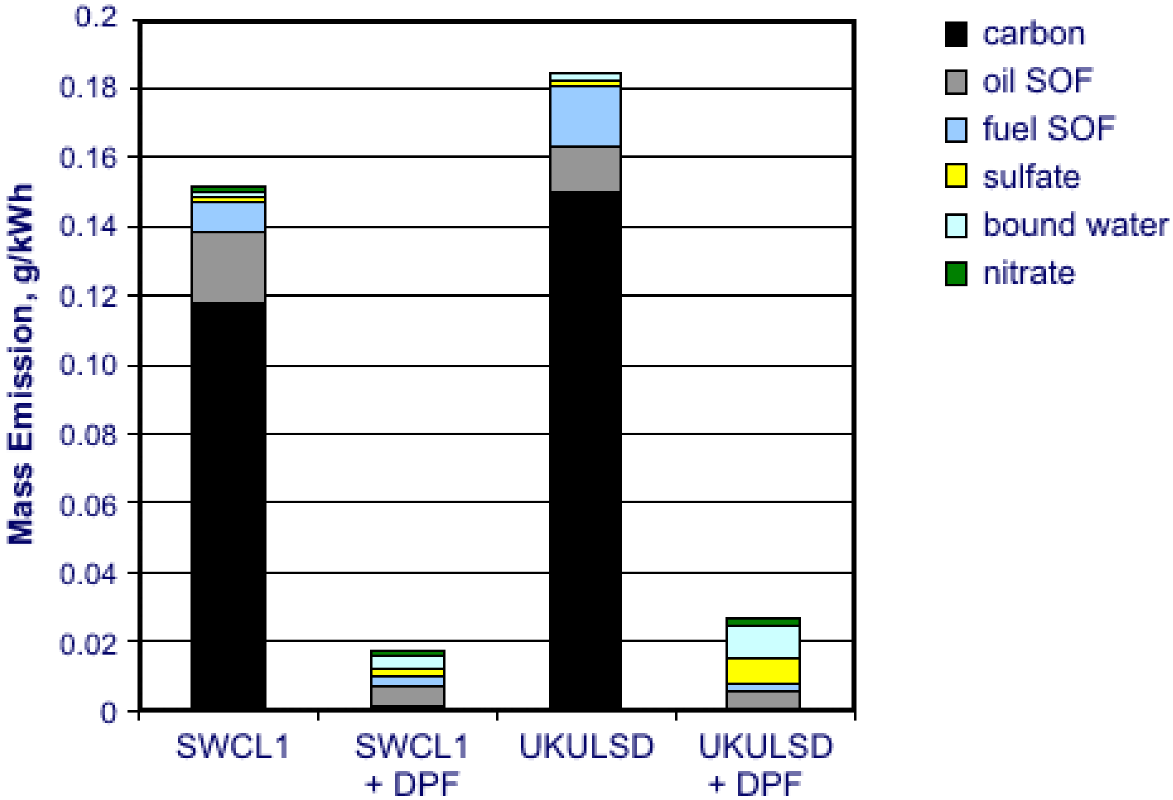

Figure 9. Effect of Particulate Filter on PM Composition

Euro 1 engine on R-49 cycle; SWCL1 (Swedish Class 1) fuel <10 ppm S; UKULSD (UK ultra low sulfur diesel) fuel - 50 ppm S

To understand the performance capabilities of diesel filters, one has to be familiar with the definition and composition of diesel particulates. Diesel particulate matter is composed of three main fractions: (1) elemental carbon and ash (solid), (2) organic fraction (SOF, liquid), and (3) sulfate particulates (liquid). The described particle deposition mechanisms are effective in collecting solid and, to a degree, liquid particles. However, a significant portion of liquid particulates, both SOF and sulfates, is in the gas phase under the high temperature conditions in the filter. The formation of liquid particles (through nucleation and condensation) occurs only after the exhaust gases are cooled down, typically in the particulate sampling equipment downstream of the particulate filter, as illustrated in Figure 10. Obviously, particle formation downstream of the trap will reduce the observed filtration efficiency.

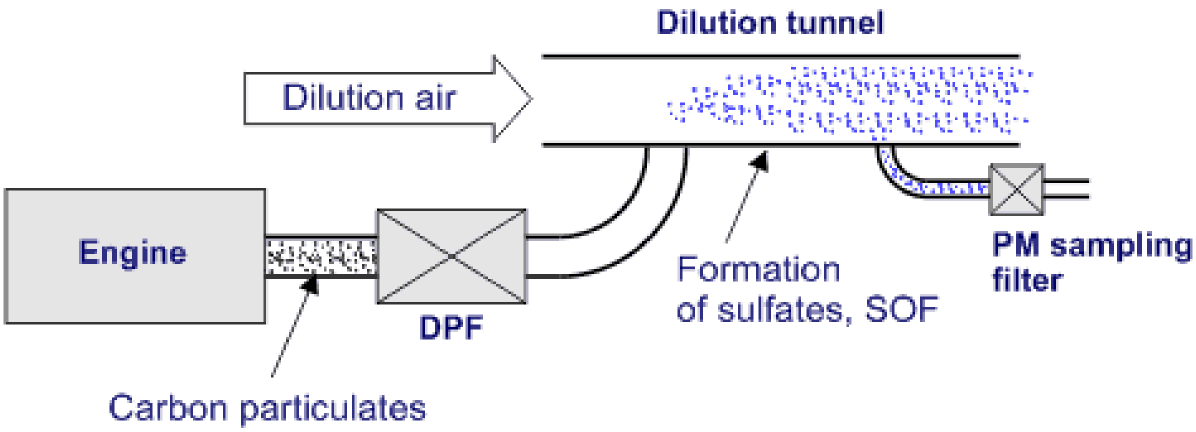

Figure 10. Formation of Liquid Particulates Downstream of DPF

The higher the filter temperature, the more of the SOF particulates pass through as vapors. Therefore, the SOF efficiency of an uncatalyzed diesel trap will decrease with increasing temperature. Most passive diesel filters incorporate catalysts which lower the soot oxidation temperature to facilitate regeneration. Since these catalysts also oxidize hydrocarbons, catalyzed filters are more effective in the removal of SOF particulates.

However, the catalyst may also generate sulfate particulates, especially at elevated temperatures and in conjunction with high sulfur diesel fuel, as discussed in "Diesel Oxidation Catalyst". Sulfate particulates are composed primarily of sulfuric acid which is formed by heteromolecular nucleation of water vapor and catalyst-generated SO_3 molecules. The nucleation occurs only at low exhaust temperatures. Thus, a high temperature diesel filter is ineffective in capturing the sulfate particulates. For this reason, catalytic diesel filters may show declining filtration efficiencies at high temperatures due to the generation of sulfate particulates. Filters utilizing oxidation catalysts of high activity must be operated on ultra low sulfur fuels (say, below 50 ppm S) to control sulfate particulate emission. If fuels of higher sulfur levels are used, the catalyst generated sulfates may more than offset the benefit in capturing the solid particulates, resulting in a negative filtration efficiency for total PM.

Performance of several types of diesel filters is discussed in following papers. The general trends are summarized in Table 1. The performance, especially that related to sulfates, depends very strongly on the fuel sulfur content and the emission test cycle (temperature).

Table 1
Typical Filtration Efficiency of Diesel Particulate Filters (PM Mass)

Fraction of diesel PM	Efficiency	Comments
Elemental carbon	95 - 99.9%	Physical filtration.
Organic fraction (SOF)	50 - 90%	Conversion primarily by catalytic oxidation, depends on temperature. Lower conversion in non-catalytic filters.

Sulfate particulates	No filtration	Catalytic oxidation of SO_2 to SO_3 can increase SO_4 causing negative efficiency when high sulfur fuel is used.
Total PM	**70 - 95%**	

The above efficiencies are based on the assumption that sulfates are included in the definition of PM, as it is the case in public health regulations. However, sulfates are not the part of diesel particulates in several occupational health regulations (Germany [BMA 2001], US non-coal mines [MSHA 2001]). According to the letter of such regulations, the generation of sulfuric acid in the filter is not considered a counterproductive process, making it possible to operate catalytic filters with high sulfur fuels (unless separate exposure limits for SO_3/sulfuric acid that may also be in place are exceeded when operating the DPF). If sulfates are neglected, total efficiency of most filter systems will be in the 85% - 95% range and above.

Particle Numbers

While most of PM mass emissions are composed of solid matter (or solid particles with adsorbed vapors), liquid material constitutes a very significant part of diesel nanoparticles, which are the main contributor to particulate number emissions. If the liquid material, including sulfates and SOF, is formed in the PM sampling system, i.e., downstream of the filter, the DPF will be ineffective in reducing nanoparticle and particle number emissions. Even worse, by retaining carbon particulates, the DPF removes the material which otherwise acts as a “sponge” for condensates formed in the sampling system. Therefore, particulate filters tend to increase the formation of nanoparticles through nucleation. In effect, DPFs reduce the numbers of mostly solid agglomeration mode particles, replacing them by mostly liquid nuclei mode nanoparticles, as shown in Figure 11 [Burtscher 2001].

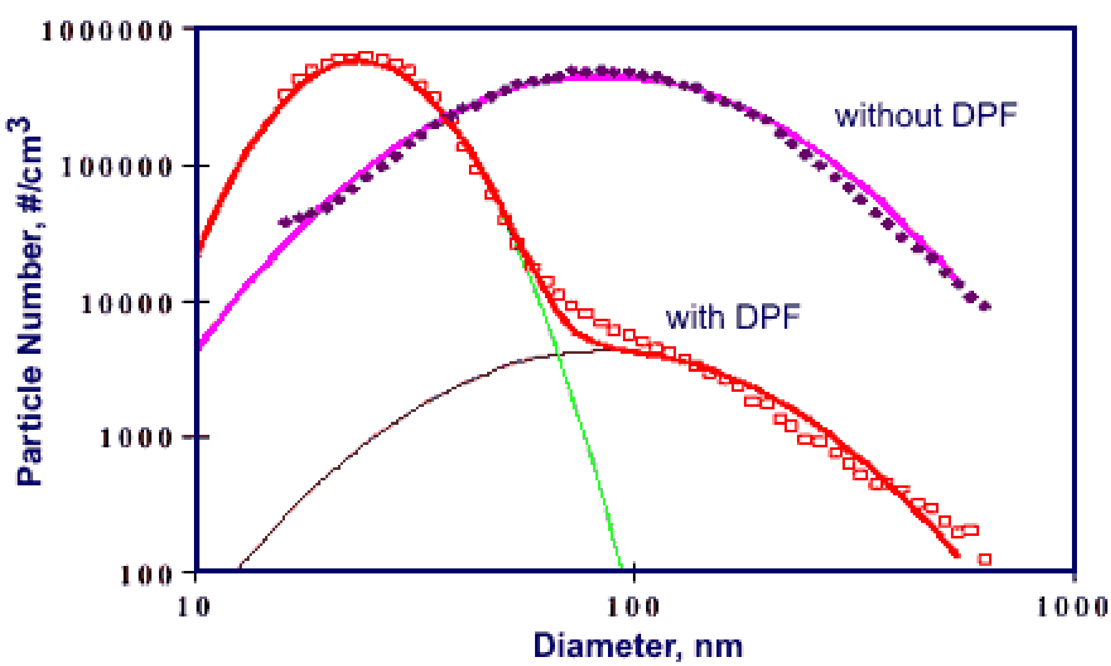

Figure 11. Typical Particle Size Distribution with and without DPF

As a result, several studies measured increased particle numbers with particulate filters, as illustrated in Figure 12 [Andersson 2001]. The data was generated on the hot ECE R-49 test cycle and with a catalytic filter system. High particle number emissions are clearly related to sulfates, which are generated at high exhaust temperatures in the catalyst, as indicated by the higher particle numbers in tests with higher sulfur content in the fuel.

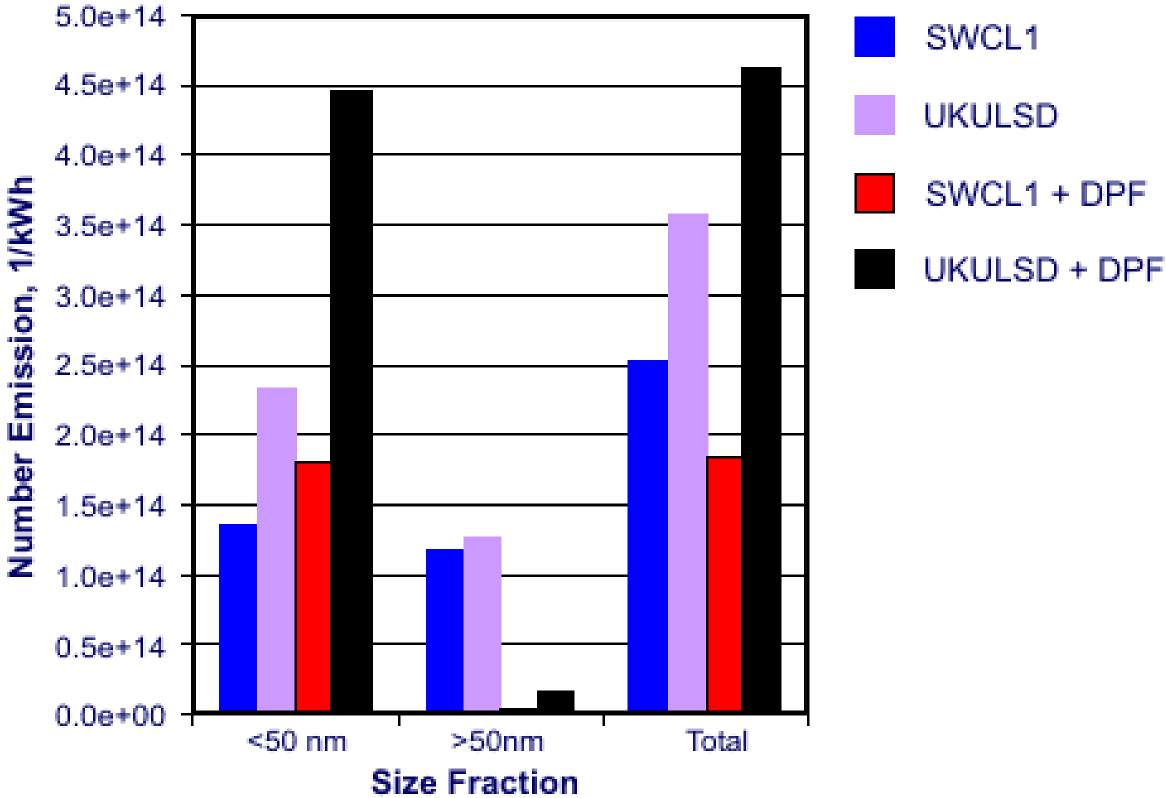

Figure 12. Effect of Particulate Filter on Particle Number Emissions

Euro 1 engine on R-49 cycle; SWCL1 fuel <10 ppm S; UKULSD fuel - 50 ppm S

In the general case, however, the impact of DPFs on particulate number emissions has to be described as inconclusive; the particle numbers may be either increased or decreased. The main parameters influencing the DPF performance or the performance assessment can be listed as follows:

- *Presence of nanoparticle precursors*. This includes SO_3/sulfuric acid which may be catalytically generated from sulfur precursors in the fuel. Hence, lower fuel sulfur content will result in less nanoparticle emission. Hydrocarbons are another nanoparticle precursor. If HCs are removed from the system, e.g., by using a catalyst, lower nanoparticle emissions may be expected. Such phenomena as adsorption/desorption of HCs on accumulated soot in the exhaust system may also contribute to the overall particle number emission.

- *Exhaust gas temperature*. Sulfate particulate are formed at high temperature conditions, such as at full engine load. Therefore, in catalytic systems, higher particle numbers will be measured over hot engine test cycles.
- *Particulate sampling parameters*. In the absence of standard measuring methods of particle number emissions, laboratories are free to choose any measuring setup and parameters. As discussed in Diesel Exhaust Particle Size, the choice of parameters, such as dilution ratios or dilution tunnel residence times, can critically influence the measurement. Measurements are particularly unstable and irreproducible in systems with high rates of particulate nucleation and condensation (as opposed to testing configurations that attempt to measure exclusively solid nanoparticles).

The above discussion was based on a quiet assumption that liquid condensates are counted as particles. As standards are being developed to quantify diesel particle number emissions, a controversy exists as to the inclusion of liquid condensates in particle number measurements [Burtscher 2001]. Several laboratories use sample conditioning techniques that “dry” the gas sample by removing volatile nanoparticle precursors before particle number measurements are taken. If particulate filters are evaluated using this technique, they show consistently good particle number reduction performance, as shown in the example plot in Figure 13 [Mayer 2000]. This is an indication that solid nanoparticles are retained with high efficiency in a variety of DPF media.

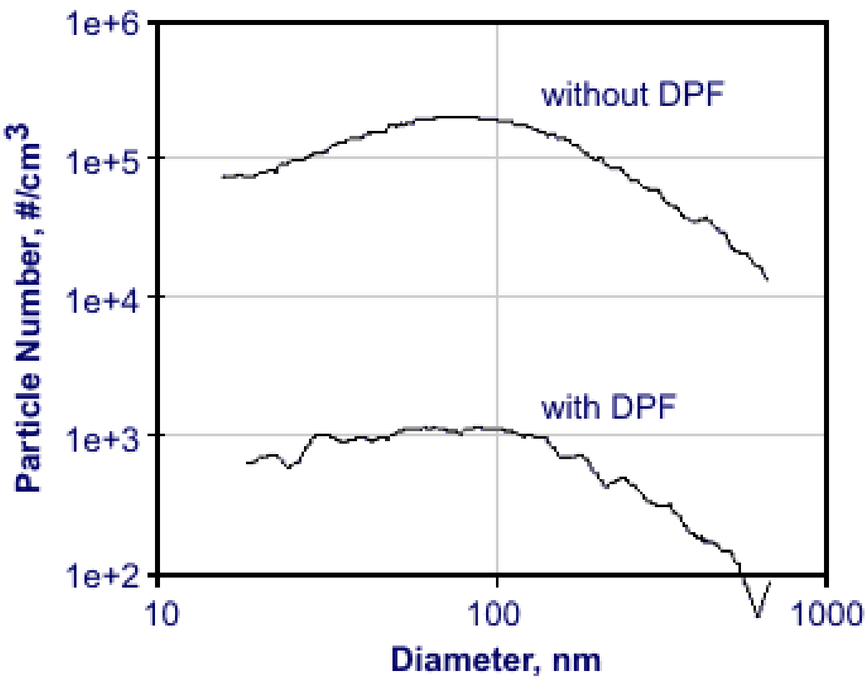

Figure 13. Particle Size Distribution with and without DPF - Solid Particulates

Ceramic monolith filter on Caterpillar construction engine

Commercial Status

The most important issue with diesel particulate filters is reliable filter regeneration. Generally speaking, today's diesel filter systems still have insufficient dependability, may experience excessively high pressure drop or clogging. Furthermore, excessive heat released during regeneration may lead to a loss of mechanical integrity and catastrophic failure of the filter material. While these issues are being addressed through intensive development efforts in the areas of filter materials and regeneration strategies, the technology has achieved a sufficient level of maturity to allow for first commercial applications on new light- and heavy-duty diesel engines.

Clean air regulatory authorities in the EU and in the US have adopted diesel emission standards that are believed to require the use of particulate filters to meet the PM limits. These standards, including the HD Euro 4, HD US 2007, LD Euro 4, and US LD Tier 2, represent tightening of diesel PM emission limits from 50 to 90%, relative to their respective predecessors. The European standards, both effective in 2005, introduce PM limits of 0.025 g/km for light-duty vehicles and 0.02 g/kWh for heavy-duty engines. The US standards come to power later than those in the EU (Tier 2: phase-in 2004-2009), but introduce even more stringent PM limits: no more than 0.02 g/mi for LD vehicles and 0.01 g/bhp-hr for HD engines. If these standards are upheld by the authorities, a wide-scale launch of particulate filters on new diesel engines for highway vehicles can be expected between 2005 and 2007.

Historically, first diesel particulate filters were introduced in 1985 on Mercedes cars sold in California [Abthoff 1985]. The traps, which utilized passive catalyzed filter technology, experienced a number of technical problems and were soon taken off the market.

After this experience the technology disappeared from new vehicles, but was quickly adapted for retrofitting of selected off-road applications, mainly in underground mining, tunneling, and material handling industry. Most mining applications took place in Australia and in the U.S., while diesel forklifts and tunneling machinery was retrofitted mainly in Europe (Germany, Switzerland, ...). In the late 1990s, once more retrofit experience was collected, several programs were launched that targeted heavy-duty highway vehicles, such as urban bus fleets. The first program of this type, known as the Environmental Zones, was started in 1996 in three major Swedish cities. Retrofit programs for diesel buses and other vehicles were subsequently adopted in other European cities (Paris, Berlin, Munich, cities in the UK), in the Far East (Taipei, Tokyo), and in the US (New York City, California).

In 2000, diesel particulate filters made their return to the automobile application. The first "new era" filter application on a diesel car was the PSA Peugeot 607 HDi 2.2 (MY2000), which came equipped with an active particulate filter system regenerated through a sophisticated strategy involving the use of fuel additive and common-rail post injection of fuel [Salvat 2000]. In 2001 this filter system was introduced on the Peugeot model 406 HDi 2.2, and then on a number of other cars powered by Peugeot engines including Peugeot 307, 807, and some Citroen C5 and C8. By the end of 2002 the PSA Group sold nearly 400,000 particulate filter-equipped vehicles [PSA 2003].

The first heavy-duty engine with a diesel particulate filter was introduced by Navistar in 2001. The engine, a 530 cu.in. displacement, 275 hp unit, was certified by the US EPA and the California ARB to the 0.01 g/bhp-hr PM standard (US 2007). Equipped with a passive catalyzed diesel filter, the engine was developed for school bus application, primarily in California.

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