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A Review on Diesel Soot Emission, its Effect and Control

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Abstract

The diesel engines are energy efficient, but their particulate (soot) emissions are responsible of severe environmental and health problems. This review provides a survey on published information regarding diesel soot emission, its adverse effects on the human health, environment, vegetations, climate, etc. The legislations to limit diesel emissions and ways to minimize soot emission are also summarized. Soot particles are suspected to the development of cancer; cardiovascular and respiratory health effects; pollution of air, water, and soil; impact agriculture productivity, soiling of buildings; reductions in visibility; and global climate change. The review covers important recent developments on technologies for control of particulate matter (PM); diesel particulate filters (DPFs), summarizing new filter and catalyst materials and DPM measurement. DPF technology is in a state of optimization and cost reduction. New DPF regeneration strategies (active, passive and plasma-assisted regenerations) as well as the new learning on the fundamentals of soot/catalyst interaction are described. Recent developments in diesel oxidation catalysts (DOC) are also summarized showing potential issues with advanced combustion strategies, important interactions on NO_2 formation, and new formulations for durability. Finally, systematic compilation of the concerned newer literature on catalytic oxidation of soot in a well conceivable tabular form is given. A total of 156 references are cited. © 2010 BCREC UNDIP. All rights reserved.

Keywords: Diesel soot emission; Diesel particulate filter; Active regeneration; Passive regeneration; Diesel oxidation catalyst

1. Introduction

Diesel engines are the workhorses for the modern society since they are widely used to transport goods, services and people. They are the power source behind commercial transport, being employed in trucks, buses, trains and ships, as well as off-road industrial vehicles such as excavation machinery and mining equipment. They also play a vital role in power generation and are used for farming, construction and industrial activities. The application of diesel engines in these fields is growing rapidly all around the globe because of the high efficiency of the engines, their low-operating costs, high durability and reliability. But the diesel engine is one of the largest contributors to environmental pollution problems worldwide, and will remain so, with large increases expected in vehicle population causing ever-increasing global emissions of diesel particulate materials (DPM) and nitrogen oxides (NOx).

Diesel exhaust differs from that of petrol engine exhaust in two major characteristics. Firstly, diesel exhaust contains a far higher amount of particulate matter, and NOx, and

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secondly, the exhaust is far leaner, that is, far less unburned hydrocarbon and carbon monoxide than a typical exhaust from petrol engines. Thus nowadays, the focus of the reduction of harmful diesel emissions is mainly on particulate matter (DPM) and NOx. DPM consist mostly of carbonaceous soot with minor components of volatile organic fraction (VOF) from unburned fuel, lubricating oil and inorganic compounds such as ash and sulphur compounds [1]. DPM are suspected for a series of adverse effects on human health [2-4], on the physiology of plants [5], environment [6], the integrity of building materials [7, 8] and regional and global climate [9]. Several review papers [3,10-23] concerning adverse effect of diesel emissions on human and animal health [3], environment [10], physico-chemical characterization of soot [11,12], particle size of soot [13], strategies to control [14,15] the DPM emissions, catalytic filters [16,17], underground mining emissions [18], impact of sulphur on emissions [19], effect of particulate traps on the efficiency of diesel engines [20], type of fuels [21], DPM sampling [22], mechanism and kinetics of soot oxidation [23] etc. have been published.

A number of Ph.D. degrees [1,22,24-28] have been awarded by various universities on the topics related to diesel emissions and control. The significant activity in the development of advanced diesel emissions control technology is also depicted in the numerous patent references [29-38].

This review is therefore summarizes and evaluates recent published information on diesel soot emissions, their effects on the environment and human health, and ways to minimize emissions and effects in a consolidated treatise.

1.1 Diesel exhaust composition

Inside an engine, the complete combustion of the motor fuels composed exclusively of carbon and hydrogen would only generate CO_2 and H_2O, to the exclusion of any other harmful product. However, the very short time allowed for chemical oxidation processes integration in combustion chambers, the lack of homogeneity in the carburetted mixtures, and the heterogeneity and rapid variations in the temperature do not allow for the state of ideal thermodynamic equilibrium to be reached. Thus, the incomplete combustion of a hydrocarbon results in the formation of a wide range of organic and inorganic compounds distributed among the gaseous, semi-volatile and particulate phases [1] as is schematized in Table 1. The gaseous phase contains CO, CO_2, NO_x, SO_x, NH_3, water vapours, volatile organic compounds (VOC), hydrocarbons (HC), polycyclic aromatic hydrocarbon (PAH), organic/inorganic acids, halogenated organic compounds, dioxins, etc.

The majority of the components are mutagens, carcinogens and toxic air pollutants and are suspected for a series of adverse effects [3-8] as mentioned in the above paragraph. Hydrocarbons, one of the major organic pollutants in diesel exhaust, are emitted as gaseous and DPM-bound compounds. The phase (gas, condensed liquid, or solid) of HC in diesel exhaust depends on their molecular weight, temperature, and concentration. Some of the vapour phase compounds that could potentially affect human health include formaldehyde, methanol, acrolein, benzene, 1, 3-butadiene, and low-molecular-weight PAHs and their oxygenated and nitrated derivatives.

1.2 Diesel particulate matter

Inside an engine, the incomplete combustion of a hydrocarbon results in the formation of DPM which consists mostly of carbon with minor components of organic compounds from unburned fuel, lubricating oil and inorganic compounds such as ash (inorganic minerals) and sulphur compounds [11]. The soot formula [39] can be approximately given as C_8H. According to Kittelson [12], typical particle composition of a heavy-duty diesel engine tested under a heavy-duty transient cycle breaks down as follows: carbon 41%; unburned fuel 7%; unburned oil 25%; sulphate and water 14%; and ash and other components 13% as shown in Figure 1. Depending on engine design and operating conditions and fuel composition the fraction associated with

Table 1. Typical diesel exhaust composition [25]

Component	Concentration
CO	100-10000 ppm
HC	50-500 ppm, C_1
NO_x	30-1000 ppm
SO_x	Proportional to fuel S content
DPM	20-200mg/m^3
CO_2	2-12 vol%
Ammonia	2.0 mg/mile
Cyanides	1.0 mg/mile
Benzene	6.0 mg/mile
Toluene	2.0 mg/mile
PAH	0.3 mg/mile
Aldehydes	0.0 mg/mile

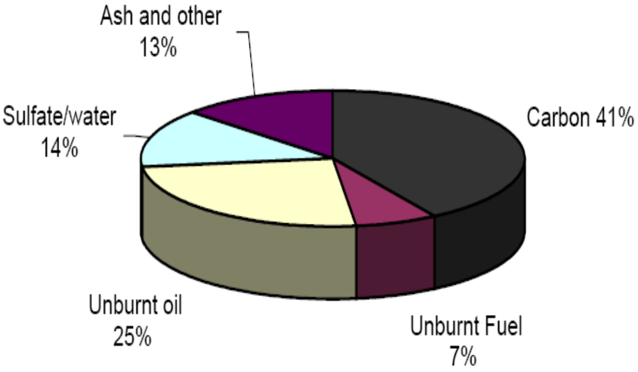

Figure 1. Composition of particles from a heavy-duty diesel engine, tested in a transient cycle on an engine test bench [12]

unburned fuel and lube oil, generally described as the soluble organic fraction (SOF) may vary widely. It can range from less than 10% to more than 90% by mass. SOF values are highest at light engine loads when exhaust temperatures are low. Common particulate bound compounds are linear- and branched-chain HC with 14 to 35 carbon atoms; poly-nuclear aromatic hydrocarbons (PAHs); alkylated benzenes; nitro-PAH; and a variety of polar, oxygenated PAH derivatives [18]. These compounds are of particular concern because several of them have been associated with carcinogenicity and mutagenicity, as reported in various laboratory studies.

Diesel pollutants are often emitted close to where people live and work. The emissions are released at ground level and are suspended in the air. The pollutants get into our bodies when we breathe. Some of the DPM are large enough to be visible as smoke while most are in the invisible sub-micrometer range. Particles differ in size, composition, solubility and therefore also in their toxic properties.

1.2.1 Classification of particulate matter

Particles may be classified as primary or secondary depending on their formation mechanism. Primary particles are directly emitted into the atmosphere through diesel exhaust. Secondary particles are formed usually by chemical reactions of gaseous pollutants, such as sulphur oxides and nitrogen oxides interacting with other compounds in the air to form fine particles. These tiny bits of soot can travel hundreds of miles downwind of the original pollution sources.

The health effects of diesel particulate have been a matter of concern for many years, because of both the chemical composition and the particle size spectrum [40]. Soot particles can be categorized in the following four sizes: (1) Large particles >10 µm, (2) Coarse particles 2.5 – 10 µm (DPM10), (3) Fine particles 1.0 - 2.5 µm (DPM2.5), and (4) Ultra-fine <1.0 µm (DPM1.0). The size of the particles also determines the time they spend in the atmosphere. While sedimentation and precipitation removes DPM10 from the atmosphere within few hours of emission, DPM2.5 may remain there for days or even a few weeks. Consequently, these particles can be transported over long distances.

Current DPM emissions legislation is based on ambient mass concentrations, mg/m^3. None of these regulations contain a reference to either the size or the number concentration of the particles. Further, the prescribed gravimetric analysis of DPM is non-specific with respect to chemical composition and aerosol properties and, thus, delivers no toxicologically relevant information. Additionally, it is the smaller particles that are proposed to be the ones most harmful to human health [41]. These concerns have led to proposals from a number of bodies, such as the German environmental agency, the UBA, that particulate emissions should be legislated not just by mass,

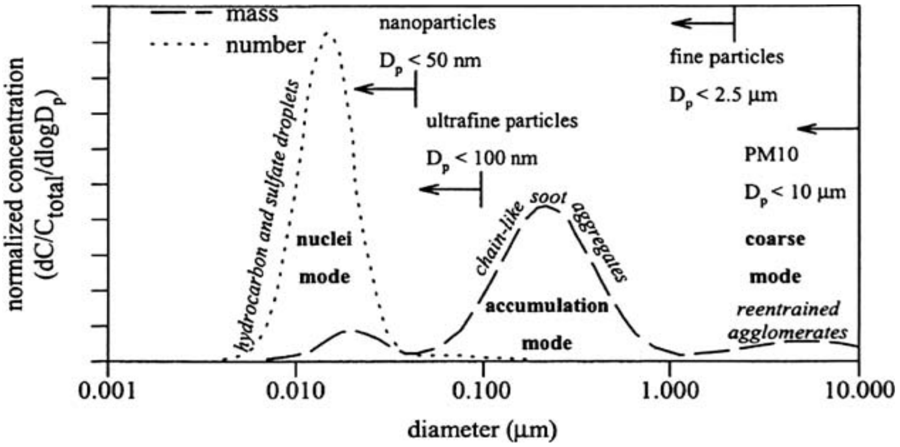

Figure 2. Schematic of mass and number based particle size distributions from diesel engines

but also by number [42]. The typical contribution of the small and large particles to the particle number and particle mass is shown in Figure 2. It is clear that the very small particles which make up the nuclei (or nucleation) mode are present in the greatest number, but contribute little to the total mass, while the relatively small number of larger particles which make up the accumulation mode dominate the particulate mass.

More than 90% of diesel exhaust-derived DPM is smaller than 1 μm in diameter [43]. Most of the mass is in the 0.1–1.0 μm "accumulation" size fraction, while most of the particles are in the <0.1 μm "nano-particle" fraction [44,13]. These small particles are respirable and penetrate deep into the lungs [45] where it is able to enter the bloodstream and even reach the brain [46]. They also can accumulate in lungs over time, obstructing oxygen transfer to the blood and causing many health problems. A given mass of very small particles contains a larger number of particles, with a correspondingly larger surface area, than an equivalent mass of larger particles. Consequently, a given mass of ultra-fine particles will impact a larger surface area of lung tissue than will an equal mass of larger particles [47] leading to more extensive exposure of the lung tissues. Coarse soot particles (2.5-10μm) are inhaled into the windpipe and settle there, causing more irritation and more coughing. Large particles, DPM10 deposit from the air into the nose, throat, and lungs, causing coughing and irritating the throat, and are ejected from the body through sneezing, coughing, and nose blowing. Larger particles come largely from windblown dust, vehicles travelling on unpaved roads, and crushing and grinding operations. In other cases, gases such as sulphur oxides and nitrogen oxides interact with other compounds in the air to form fine particles. Above mentioned phenomenon is depicted in Figure 3.

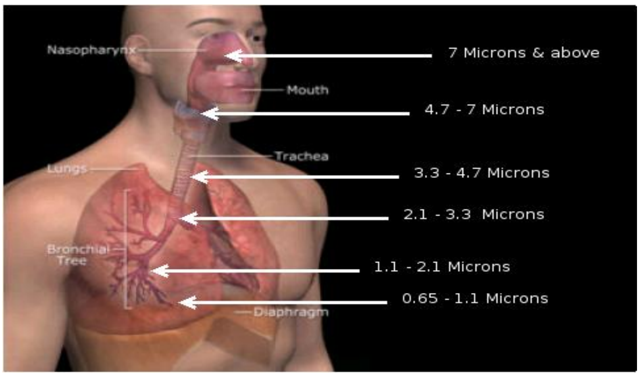

Figure 3. Transport of the DPM with breath according to their size

1.3 Adverse effect of soot

Diesel soot emissions contribute to the development of health problems; pollution of air, water, and soil; soiling of buildings; reductions in visibility; impact agriculture productivity, global climate change, etc.

1.3.1 Effect of soot on human health

Many toxicological and epidemiological studies established adverse health effects by particulate matter (DPM10, DPM2.5) indicate that exposure of diesel exhaust have been linked with acute short term problems such as irritation of the eyes, nose, and throat vomiting, light-headedness, headache, heartburn, numbness, bronchitis, chronic respiratory, cardiovascular, cardiopulmonary and allergic diseases such as shortness of breath and painful breathing, cancer, and premature death. Some investigations indicate that particles can induce inheritable mutations [48]. Potential health impacts of DPM, ozone and carbon monoxide formed from diesel emissions on newborn children include birth defects, growth retardation and sudden infant death syndrome.

Diesel exhaust contains a variety of confirmed carcinogenic compounds such as formaldehyde, acetaldehyde, dioxins and polycyclic aromatic hydrocarbons (PAHs) [10]. Over 30 epidemiological studies link diesel exhaust to lung cancers [49]. Studies have also linked diesel exhaust to bladder cancer. On average, long-term occupational exposures to diesel exhaust were associated with an increase of ~ 40% in the relative risk of lung cancer. Population-based case -control studies identified statistically significant increases in lung cancer risk for truck drivers, rail, road workers and heavy equipment operators.

Several organizations have reviewed [50] epidemiologicand experimental studies related to diesel engine exhaust and lung cancer, and they have classified (or proposed classifying) exhaust emissions as 'potential', 'likely', 'probable', or 'definite' carcinogens for humans (National Institute for Occupational Safety and Health, NIOSH); International Agency for Research on Cancer (IARC); Health Effects Institute (HEI); World Health Organization (WHO); California EPA; US EPA. Apart from the health problems the soot combines with other air pollutants and forms atmospheric brown clouds (ABCs) which cause numerous adverse effects.

1.3.2 Effect of soot on animal

Long term studies looking at the effect of diesel emission exposure in rats have demonstrated increased accumulation of particles and aggregates of particle laden macrophages in the alveoli and per bronchial interstitial tissues as well as local inflammation, epithelial proliferation, fibrosis and emphysematous lesions. Diesel emissions are associated with reproductive system impacts in animals. Pregnant rats exposed to diesel emissions resulted in elevated testosterone in the mother and reproductive organ changes such as masculinization of fetuses. Animal studies suggest diesel emissions may affect the immune system, including reduced immunity to bacterial infections in the lung [51].

1.3.3 Effect of soot on vegetations

Particulate deposition and effects on vegetation unavoidably include (1) nitrate and sulphate and their associations in the form of acidic and acidifying deposition and (2) trace elements and heavy metals [52]. Atmospheric diesel DPM impact agriculture productivity in a variety of ways: 1) reduction of solar radiation in turn reducing photosynthesis, 2) settling of soot particles on the plants can shield leaves from solar radiation hindering photsynthesis, 3) soot deposition can increase acidity and cause plant damage, and 4) reduction of rainfall by dimming induced by soot. It causes all type of injury in plants such as epinasty, nicrosis, chlorisis, abscission, flower dropping, etc.

1.3.4 Effect of soot on water and soil pollution

Atmospheric deposition of air pollutants released from diesel exhaust to ecosystems and their components, such as forests, water bodies, and soils, is another significant source of contamination [53]. Water and soil are contaminated indirectly by dry and wet deposition of diesel exhaust emitted to the atmosphere. Wet deposition dominates the transfer of airborne contaminants to the Earth's surface, but dry deposition may be important in arid areas where ambient concentrations are high and rainfall is limited. In urban areas, sedimentation of large particles is more important than wet deposition and dry gaseous and small particle deposition [54]. Environmental effects of atmospheric deposition have been studied for a long time, but the mechanism is poorly understood [53]. Enhanced levels of atmospherically deposited nitric and sulfuric acid (acid rain) adversely affect the health of ecological systems, such as agricultural crops, large water bodies, and forests. Arimoto [53] concluded that deposition is the dominant source for a variety of chemical contaminants in the Great Lakes. Atmospheric deposition provides most of the dissolved inorganic and total nitrogen in the nutrient load of the lakes and is responsible for water nitrification and forest damage [55] Atmospheric wet deposition to a high-elevation forest at Whiteface Mountain, NY, was 12 times more efficient at transferring nitrogen to the forest canopy than was dry deposition [56]. Heavy metals, PAHs, and dioxins common to diesel exhaust can be transported long distances as gases or DPM. They are often resistant to degradation and are found in relatively high concentrations in many rural and remote areas. Simcik et al. [57] and Wik and Renberg [58] reported higher atmospheric loading of PAHs in lake sediments in Michigan and Sweden, respectively. Schroder et al. [54] reported that wet deposition accounted for 85% of the total deposition of toxic materials in a terrestrial ecosystem. PAHs and dioxins have also been detected in German forest canopies.

1.3.5 Effect of soot on materials

The deposition of airborne soot on the surfaces of buildings, tunnels, highway bridges, and monuments of historical importance like Taj Mahal in India can cause damage and soiling, ventilation system blackening, thus reducing the useful life and aesthetic appeal of such structures. Diesel exhaust builds up in tunnels and underground garages where [59] it is difficult to remove. Soot promotes metal corrosion [60]. Many metals form a film that protects against corrosion; however, high concentrations of anthropogenic pollutants lessen the effectiveness of the protective film.

1.3.6 Effect of soot on visibility

Visibility degradation (or haze) is caused by both primary and secondary particles emissions. It is measured as the light extinction coefficient, which is the natural logarithm of the fractional reduction of light transmission per unit distance, usually expressed as Mm^{-1} (inverse mega-meters) [61]. Light extinction consists of scattering and absorption by gases and particles [62]. Clean air scatters light with ~12 Mm^{-1} at sea level, and NO_2 is the only gaseous pollutant that appreciably absorbs light. Particle light scattering depends on the particle size distribution, which can shift as hygroscopic chemical species absorb water with increasing humidity [63]. Light absorption is mostly due to ABC. Visibility reduction causes accidents on the roads.

1.3.7 Effect of soot on environment and global warming

Atmospheric soot envelopes most part of the globe with a dense layer of brown clouds. A series of investigations [64] pointed out that soot in air pollution affects agriculture, water budget and climate at the local, the regional and the global level. Soot may cool or warm, depending on whether it is airborne or deposited. Atmospheric soot aerosols directly absorb solar radiation, which heats the atmosphere and cools the surface. Regionally (but not globally), as much as 50% of surface warming due to greenhouse gases may be masked by ABCs [65]. The soot settling on glaciers or ice in arctic region absorbs solar heat directly; contribute to melting of Himalayan glaciers [66] and causing ice to melt. This can lead flooding, rise in water level of sea. Many low lying areas near cost will get submerged with water. The atmospheric solar heating by soot, next to carbon dioxide, is the major contributor to global warming [67].

Global dimming, a gradual reduction in the amount of global direct irradiance at the Earth's surface, has partially counteracted global warming from 1960. The main cause of this dimming is aerosols produced by volcanoes and pollutants. These aerosols exert a cooling effect by increasing the reflection of incoming sunlight. James Hansen and colleagues [68] have proposed that the effects of the products of fossil fuel combustion-CO_2 and aerosols-have largely offset one another in recent decades, so that net warming has been driven mainly by non-CO_2 greenhouse gases.

The influences of aerosols, including soot, are most pronounced in the tropics and sub-tropics, particularly in Asia, while the effects of greenhouse gases are dominant in the extra-tropics and southern hemisphere. Clouds modified by pollution have been shown to produce less drizzle, making the cloud brighter and more reflective to incoming sunlight, especially in the near-infrared part of the spectrum [69].

1.4 Diesel emissions legislation

Due to the adverse effects of diesel emissions on health, environment, vegetations, materials, climate, etc.; Government legislations for permissible exhaust emission standards [70] were first introduced in both Europe and the United States of America in 1982, only for light-duty vehicles and not until 1990 for heavy-duty engines. The first Indian emission regulations [71] were idle emission limits which became effective in 1989. These idle emission regulations were soon replaced by mass emission limits for both gasoline (1991) and diesel (1992) vehicles, which were gradually tightened during the 1990's. Since the year 2000, India started adopting European emission and fuel regulations for four-wheeled light-duty and for heavy-duty vehicles. Emission regulations of DPM and NOx have become more and more stringent as indicated in Table 2. The limits are defined in mass per distance (g/km, light-duty vehicles) or mass per energy (g/kW h, heavy-duty engines) over a defined test cycle. Because of greater air pollution problems, California has its own, more stringent standards. The trends in the DPM legislation apparent in the table make it clear that effective emissions control devices need to be developed to enable vehicles to meet the increasingly stringent limits [72]. Up-to-date information of the various diesel emission standards and vehicle certification tests can be found on the Internet [73].

2. Emissions control technologies for diesel engines

Various primary measures (modification in engine, fuel, operating parameters, etc.) for diesel engine exhaust pollution control have failed to match the requirement being put forward by regulatory stipulations in different developed and developing countries of the world. Therefore, following secondary emissions control technologies have been proposed and being adopted as an end-of-the pipe treatment technologies:

Table 2. Emission standards for diesel vehicles

Year	Reference	Light duty diesel (g/km)		Heavy duty diesel (g/kWh)	
		NO_x	DPM	NO_x	DPM
2000	Euro I India 2000	-	0.14-0.25	8.0	0.36
2005	Euro II Bharat Stage II	-	0.08-0.17	7.0	0.15
2008	Euro III Bharat Stage III	0.50-0.78	0.05-0.10	5.0	0.10
2010	Euro IV Bharat Stage IV	0.25-0.33	0.025-0.04	3.5	0.02
2011	Euro V	0.18-0.235	0.005	0.235-0.28 g/km	0.005 g/km

A) Technologies for DPM, HC and CO control
- Diesel oxydation catalysts (DOCs)
- Diesel particulate filter (DPF)
- Fuel borne catalyst (FBC)

As the CO and HC emissions from diesel engines are low, they are further reduced by these technologies in addition to the particulate matter (DPM). Reducing NOx is more complicated in a diesel engine; some new technologies are now available

B) Technologies for NOx control
- Exhaust gas recirculation (EGR),
- Selective catalytic reduction (SCR),
- Lean NOx traps (LNT) and
- NOx adsorber catalysts (NAC)

2.1 Technologies for DPM, HC and CO control

2.1.1 Diesel oxidation catalysts (DOCs)

The first contribution to the reduction of particulate mass emission has been the use of the so-called DOCs [74], become mandatory for new diesel-engine cars in 1996 in the US and in 1998 in Europe. The DOC is a non-filter-based open monolith (flow through) system resembling the conventional catalytic converters for gasoline engines (Figure 4) with some significant variation to the catalyst composition so as to optimize the catalyst activity under lean conditions. The noble metals are impregnated into a highly porous alumina washcoat about 20-40µm thick that is applied to the passageway walls [1]. Most of the oxidation catalysts used in the international market contain Pt and Pd in a ratio of about 5/2 at a typical loading of 50-70 g/ft^3. DOC oxidizes hydrocarbons (HC), carbon monoxide (CO) and the volatile organic fraction (VOF) of particulate matter (DPM). Soot oxidation takes place on the filter walls of the particle filter where the catalyst has been deposited. While oxidation catalysts convert the VOF component of the DPM, the carbon component passes through them unconverted. Emissions reductions from DOC use is estimated to be around 60-90% for HCs and CO, and 20-40% for DPM which reflects the usual level of VOC in diesel DPM. A DOC can work at sulphur levels higher than 500 ppm, but there is a risk that sulphur contained in the fuel will also oxidize and form sulphate and thus actually increase the total emissions of particulate matter.

2.1.2 Diesel particulate filter (DPF)

To meet the emissions legislation the most widely used approach is to trap DPM in a porous wall flow diesel particulate filters, usually made of either cordierite ($2MgO$-$2Al_2O_3$-$5SiO_2$) [75] or silicon carbide (SiC) [76] honeycomb structure monolith (Figure 5). The adjacent channels of the honeycomb are alternatively plugged at each end in order to force the diesel aerosol through the porous substrate walls, which act as a mechanical filter

The filter walls are designed to have an optimum porosity, enabling the exhaust gases to pass through their walls without much hindrance, whilst being sufficiently impervious to collect the particulate species (Figure 6). These filters have DPM trapping efficiencies of almost 100%, making it possible to remove the particulate species from the exhaust stream [15]. As the filters accumulate DPM, it builds up backpressure that has many negative effects such as decreased fuel economy and possible engine and/or filter failure [20]. To prevent these negative effects, the DPF have to be regenerated by oxidizing (i.e. burning) trapped DPM. Filter control capabilities: DPM 80% to 90% reduction, CO > 75% and HCs > 85%.

2.1.2.1 Regeneration of DPFs

Numerous regeneration techniques have been suggested in the past [32-34, 77]. There are two basic approaches to burn the trapped DPM; these are active regeneration and passive regeneration of DPFs.

In an active regeneration of DPF, particulate matter is oxidized periodically by heat as soon as the soot loading in the filter reaches a set limit (about 45%) indicated by pressure drop across the

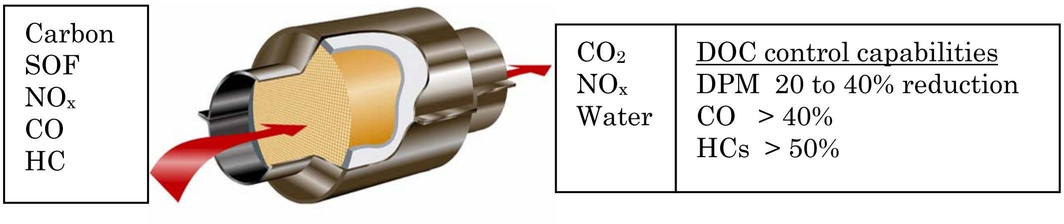

Figure 4. Flow-through diesel oxidation catalyst

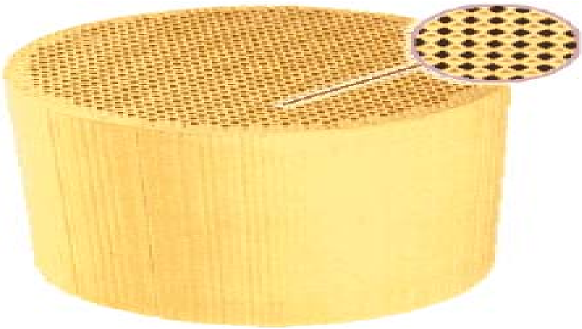

Figure 5. Ceramic monolith

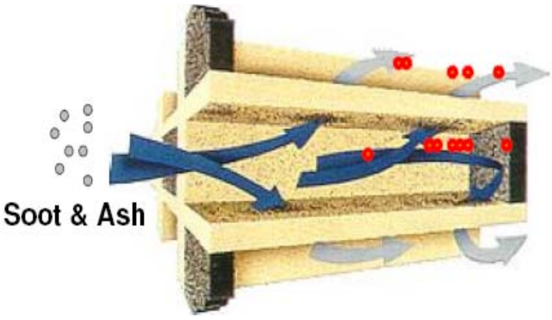

Figure 6. Wall-flow filter

DPF monitored by back pressure sensor [15]. Heat is supplied from outside sources, such as via an electric heater [78] or a flame-based burner [79] to burn soot captured in the filter by temperature rise above 600 ^{0}C. Active system entails serious stability problems for the filter materials, since temperatures as high as melting point of the filter [80] can be locally reached when the soot is burned suddenly. In addition, thermal regeneration consumes large amounts of energy. Rather, regeneration of diesel particulate filters at lower temperature is preferred. Such regeneration can be accomplished with the assistance of catalysts either deposited on the filter media [81] or fuel borne [82] at temperatures lower than 600 °C. PSA Peugeot-Citroen was the first car manufacturer that commercialised such a system for serial production [83]. It is composed of a wall flow silicon carbide filter, an oxidation catalyst in front of the filter, ceria-based fuel-borne catalyst, and sophisticated engine management system and sensors. Active regeneration DPF control capabilities: DPM by 85% reduction.

In passive regeneration of DPF, the soot is oxidized out of the filter by an ongoing catalytic reaction process that uses no additional fuel. Continuous self-regeneration of DPF occurs at the exhaust gas temperature, by catalytic combustion promoted by depositing suitable catalysts within the trap itself. The entire process is very simple, quiet, and effective and fuel efficient. That is, neither the vehicle operator nor the vehicle's engine management system has to do anything to induce the regeneration of the DPF [15]. The major challenge lies in finding catalysts capable of decreasing the soot combustion temperature from 600 ^{0}C to the temperatures normally reached at diesel exhausts (150-400 ^{0}C). Most of the catalysts used in the international markets are noble metal based (Pt, Pd), which are expensive and due to a low abundance vulnerable to further price increases upon increasing demand. Therefore, the searches for catalysts free of or low in noble metals are of global importance. Passive regeneration DPF control capabilities: 90% P M reduction, 85% CO reduction and 95% HC reduction.

2.1.2.2 Partial-flow filters

Partial-flow filters (Figure 7) are also available in various materials from fibre-based to metallic. The metallic partial flow filter uses a special perforated metal foil substrate with a metal 'fleece' layer so that the exhaust gas flow is diverted into adjacent channels and the particles are temporarily retained in the fleece before being burnt by a continuous reaction with the NO_2 generated by an oxidation catalyst located upstream in the exhaust. The advantages [84] of partial-flow filters are: no back pressure builds up as this is an open system, no external electronic control unit is required, fuel penalty is nil, regenration is passive, continuous and maintenance free. Partial Flow Filters control capabilities: DPM 30-85% on gravimetric basis and approximately 90% on nano particles, HC and CO>50%.

2.1.2.3 Continuously Regenerating Trap (CRT)

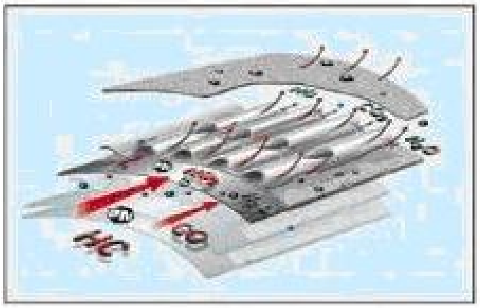

Figure 7. Partial flow diesel particulate filter

It is difficult to simultaneously remove the NOx and soot using this technology in the actual diesel engine due to the poor low-temperature activity of the catalyst. Based on the C-NO_2 reaction, the concept of so-called Continuously Regenerating Trap (CRT) has been pioneered by researchers form Johnson Matthey [85]. The mechanism of the CRT is that a diesel soot oxidation catalyst installed upstream of a wall-flow monolith diesel soot filter can oxidize NO to NO_2. Subsequently NO_2 reacts with the deposited soot on the filter to form CO_2 and NO. As a result, the trap can be continuously regenerated. Recently researchers have coated the noble metals on the ceramic or metal foam filter so the reactions can occur in the integrated systems. In this case, however, NO_2 slip will occur.

In order to solve this problem, Moulijn et al. [86] developed the TU Delft catalytic filter, in which Pt/ceramic foam is installed upstream of a wall-flow monolith. The filter configuration is capable of employing two stages of filtration: deep bed filtration in the foam and surface filtration on the wall-flow monolith. At the same time, two modes of soot oxidation reactions operate. In Pt/ceramic foam the oxidation of NO to NO_2 and multiple NO_2-soot reactions take place, while part of NO_2 will be released as NO_2 slip. The slipped NO_2 subsequently will be used to oxidize the trapped diesel soot particulate on the latter wall-flow monolith. This system improves the use of NO_2 and lowers the NO_2 slip. It was also found that the presence of water was beneficial for the NO_2-soot reaction [87]. For a reliable CRT technology, a sufficient amount of NO is required for the formation of NO_2, which then oxidizes soot. Therefore, this technology is more applicable for heavy-duty diesel vehicles. The problem of this technology is that the NOx was not actually reduced.

The NOx-aided continuously regenerated trap (NOx-aided CRT) for trucks and buses as invented by Cooper and Thoss [88]. It consists of a wall-flow monolith with an upstream flow-through diesel oxidation catalyst, which is called, in this context, the preoxidizer. Figure 8 provides a schematic representation of the system. The oxidation catalyst converts 90% of the CO and hydrocarbons present to CO_2 and 20–50% of the NO to NO_2 [89]. Downstream, the particles are trapped on a cordierite wall-flow monolith and subsequently oxidized by the NO_2.

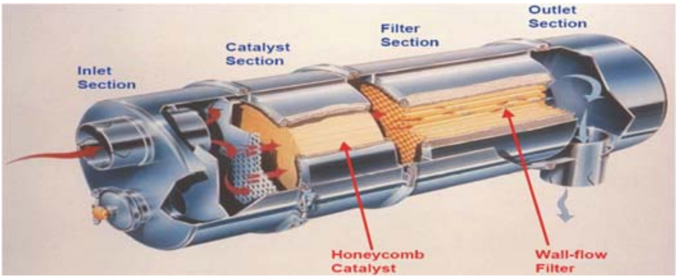

Figure 8. Illustration of NO_x-aided CRT

2.1.2.4 Advantages of the NOx-aided CRT system

The NOx-aided CRT system is an effective catalytic filter that oxidizes all carbon components in diesel exhaust gas, including small particles, and unregulated compounds [90], and it reduces the NOx concentration by 3–8% [89]. It is a simple concept that allows for fit-and-forget usage. The temperature window of 200–450 ^{o}C [89] is very reasonable; 200 ^{0}C is needed for CO and hydrocarbon oxidation [84], whereas 450 ^{0}C relates to the chemical equilibrium between NO and NO_2, which is not favorable above 450 ^{0}C [88]. Because of continuous regeneration, extreme temperatures are avoided, which enhances stability; a satisfactory performance during 600,000 km [91] has been reported.

The modular design of the separated and detachable preoxidizer and filter facilitates a high flexibility of the system, which is a great advantage for retrofitting of different buses and trucks. In each case, the optimal trap and preoxidizer can be chosen, which can, in many cases, save space, heat loss, backpressure, and system costs. Another advantage of the modular design with clamshells is that the canning can be easily opened in order to remove deposits of inorganic ash.

The filter should produce a surplus of NO_2 in order to compensate for time periods in which the temperature is too low for regeneration. The surplus NO_2 should not be too high because NO_2 is foul smelling in the vicinity of the vehicle, where it has not yet been diluted sufficiently with ambient air. For the environment, the NO_2 gives no additional problems, because NO is converted to NO_2 anyway in short time scales [89].

2.1.2.5 Limitations of the NOx-aided CRT system

The system has not yet been introduced on a wide scale because it requires the use of low-sulfur fuel [< 50 ppm [91], because SO_2 restricts the performance and when oxidized by the platinum catalyst, it adds up significantly to the total particulate mass. Low-sulfur fuel can easily be made available to public transport companies, which often have their own diesel depots, but for many other heavy-duty applications, that is not practical yet. In a few years time, this will, however, change, when low-sulfur fuel becomes widespread in Europe and the United States. Problems may arise for international transport companies that operate in countries that will not introduce low-sulfur fuels on the short term. Another problem of the system is its dependency on NOx, because it is uncertain if the required NOx-to-soot ratio for successful regeneration will be met in future engines.

2.1.3 Plasma regeneration systems

This is a more advanced regeneration system capable to reduce DPM attaining low oxidation temperatures. The oxidation behaviour of soot in air that have been ionised by an electric arc (thermal plasma) at temperatures in the range from 200 to 450 ^{0}C was investigated by Levendis et al [92]. It was found that the oxidation rate might increase more than 100%. This is attributed to some reactive species generated in plasma, such as O and OH radicals or NO_2 that facilitate the oxidation of soot particles at low temperatures. Two reactor configurations have been proposed to achieve this objective in a plasma device: Two-stage reactor, where a “classic” diesel particulate filter (DPF) is positioned downstream of the plasma generator. Such a configuration is described in a patent by Johnson Matthey [93]. The role of plasma in the two-stage configuration is to generate NO_2 and, possibly, ozone, which can oxidize particulates in the downstream filter. However the applicability of the system by itself is questionable, due to the production of NOx. In order to attain simultaneous reduction of particulates and NOx, a NOx reduction catalyst downstream of the filter is needed.

2.1.4 Fuel borne catalysts

A novel dosing system for FBC, used to assist regeneration with a DPF, has been developed. The system was designed for on-board vehicle use to overcome problems encountered with batch dosing systems. Important design features were simplicity, to minimise system cost, and the use of in-line dosing rather than batch dosing linked to tank refuelling. The development of the dosing system which continuously doses FBC into the fuel line feeding the engine injection pump [94]. The theoretical considerations behind the concept are explored, together with the realities imposed by fuelling regimes in which a variable proportion of the fuel flowing through the injection pump is passed back to the fuel tank. Two types of system are considered, ie where (i) FBC is added to the fuel in direct proportion to the flow rate of fuel and (ii) FBC is added at a constant time-based rate. The test work demonstrated that the in-line FBC dosing concept could achieve reliable regeneration with either system. The averaging effect of soot accumulation over time on the ratio of metal to soot within the DPF apparently accounts for successful regeneration despite big variations in FBC concentration. Data loggers indicated successful operation on several vehicles over distances ranging from 12,000 to 20,000 km. An in-line FBC dosing system was also fitted to a heavy duty fire appliance support vehicle for additional tests.

As a catalytic means of deliberately lowering the ignition temperature of soot into the typical range of diesel engine exhaust temperatures, doping the fuel with a metal catalyst has proven to be commercially viable and effective. Despite inevitable disadvantages such as incomplete filter cleaning from retained ash components, fuel-borne catalyst (FBC)-assisted re-generation for DPFs presents a number of advantages over direct thermal regeneration, including additional energy savings and higher trap material reliability [95]. The two most popular technologies to decrease the soot oxidation temperature and, thereby, the energy requirement are: (i) catalysed soot filter that converts NO to NO_2 which in turn oxidises soot [96], and (ii) FBC, that oxidises the soot mainly with O_2 as well as to some extent with NO [97]. The soot oxidation with oxygen is insignificant in a catalysed soot filter; this mainly arises due to from the poor contact between the catalyst and the soot [98].

2.1.5 Catalysts used for DPF

Two factors that affect catalyzed soot oxidation are the type of catalyst and the soot catalyst contact [99]. Mainly two types of catalysts have been recommended for coating the DPF for oxidation of soot:

- Platinum group metals (PGM) catalysts, and
- PGM-free catalysts.

Catalyst-soot contact is a key element for the oxidation of soot. Some catalytic elements are mobile enough under reaction condition to ‘wet’ the soot surface and effectively disperse their activity and move to non-reacted soot. Other catalysts remain as discrete particles but are mobile enough to maintain contact with the soot. More static catalytic elements require the soot to contact them. Van Setten et al. has described two modes of soot catalyst contact, loose and tight [99]. For experimental studies the soot-catalyst mixture, in an appropriate ratio, are milled in an agate mortar for “tight contact” or mixed carefully with a spatula for “loose contact”. Loose contact mode is found to best simulate contact of soot and catalyst in a DPF environment. Tight contact provides higher reaction rates and may correspond closer to certain types of DPM oxidation catalyst, such as fuel borne catalysts [99].

2.1.5.1 PGM catalysts

Various scientific studies of noble metals such as Pt, Pd, Rh, Ru were performed, however, these are found predominantly in the patent literature [100]. The most commercial and most active noble metal based filter uses Pt, usually combined with promoters, known to be active to oxidize CO and HC. The disadvantages of Pt are its high cost and production of sulfate particulates. Therefore its application is limited when using fuels containing high S contamination.

PGM catalysts are very active for the soot oxidation reaction [88,101] and especially so for nitrogen oxide containing streams. Cooper and Thoss [88] observed and reported Pt promoting soot oxidation indirectly. The combustion mechanism involved a two step process in which the NO present in exhaust gas is converted into the active oxidant NO_2 over the Pt catalyst [102, 88]. This NO_2 subsequently oxidizes soot [88] at a temperature of about 280 to 480 ^{0}C [107] at a faster rate than oxygen and is used in current DPF technology for regeneration. The authors showed that the contact between soot and Pt placed upstream of the particulate trap is not a precondition. Neri et al. [101] reported that the high activity of Pt supported on γ-Al_2O_3 in air, even at low loadings of the noble metal, is explained by the spillover effect. Pt features high activity for oxidation of SO_2 to H_2SO_4, which is a drawback. The addition of Pd to Pt significantly reduces the selectivity, and tests on Rh, Ir, and Ru exhibit selectivity near zero, due to their poor NO oxidation activity [88].

An example of a Pt loaded catalyst developed by Engelhard consists of 5-150 g ft^{-3} Pt/Rh at 5:1 weight ratio and of 30-1500 g ft^{-3} MgO support [104]. The regeneration temperature of a filter coated with the catalyst lay between 375 and 400 $^{\circ}$C. The addition of Rh reduced SO_2 oxidation. Whereas 51% of SO_2 is converted to SO_3 by 100% Pt, only 13% conversion is achieved by a combination of Pt/Pd at a weight ratio of 5:1. However, although Pd effectively reduces the SO_2 oxidation, the addition of Rh to Pt significantly increases the filter regeneration temperature [105]. The total DDPM emissions can be controlled by a catalyst with high Pt loading, only when ultra low S fuel is used, therefore, in order to obtain high DPM conversion efficiency in the Pt catalyzed filter the S content has to be minimized while NO oxidation should be maximized. In contrast some authors reported a slightly increased soot oxidation rate in the presence of SO_2 for the Pt catalyst [101, 106].

The effect of a Pt supported catalysts on soot oxidation was intensively studied by Uchisawa and coworkers [107]. The catalytic activity was estimated using TPO by detecting the temperature of the CO2 signal maximum. Numerous support metal oxides [108] were impregnated with different Pt precursors [109] to determine the catalytic activity. $Pt(NH_3)_4(OH)_2/MO_x/SiC$ ($MO_x = TiO_2$, ZrO_2 and Al_2O_3) showed relatively high oxidation activity and durability at high temperatures and with exposure to sulfate. The authors suggested that the supports with low basicity had reduced the affinity toward SO_3.

The effect of V on Pt based catalysts for the reduction of diesel emissions was studied under SO_2 conditions, for example by Kim et al. [110] and Liu et al. [111]. V is known to reduce the sulphate in diesel oxidation catalysts. Kim and coworkers found that SO_2 molecules adsorb onto the hydroxyl groups of TiO_2, and are promoted by V_2O_5 [112]. The SO_2 migrate to Pt particles and react with oxygen adsorbed onto them. Another example of using the combination of Pt and V is the catalysts developed by Sud-Chemie [93]. They applied a Pt/Mg/V catalyst coated onto a W doped TiO_2 washcoat. The Pt/V catalyst may reduce sulphate, due to the effect of V as a sulphate suppressant. Regeneration of the soot loaded filter took place at a temperature of 350 °C. The TiO_2 washcoat was favoured over Al_2O_3 to avoid interaction between Mg and Al_2O_3, resulting in a loss of surface area and catalyst deactivation. Davies and coworkers [113] found that washcoat selection is most important for the catalytic activities of supported Pt and Pd.

2.1.5.2 PGM-free catalysts

A considerable amount of research has been carried out in recent years to develop cheaper and efficient non-noble metal catalysts and

Table 3. Recent literature review at a glance on soot oxidation catalyst

Ref	Cat/precursor/Pre.method	Experimental	Operat.parameter	Remarks
137	Ag-doped (1-10%)CeO_2, ZrO_2 , Al_2O_3.Nitrate salts, Wet impregnation.	TPO & TGA Soot/cat=1/20, Tight contact. 25mg	Heated at 10 ^{0}C/min in air.N_2 with 6% of O_2 at 400 ml/min.	Ceria stabilizes silver in the oxide state Ti =227, T50% = 333 ^{0}C. Ag (5 Wt%) an excellent catalyst.
138	CeO_2–K Nitrate salts Impregnation.	TPR Soot/cat=1/10 Loose contact.	Heated at 10 ^{0}C/min in air.	KCl (40%) into CeO_2 lowest Ti=334 ^{0}C. KCl is the best promoter.
139	$CuZrO_2$, KNO_3ZrO_2, Nitrate salts Impregnation.	TPO Soot/cat=1/10,loose contact	Heated at 2 ^{0}C/ min.1500 ppm NO + 8%O_2 flow 50 ml/min.	Activity of Cu(5wt%)ZrO_2 catalyst is favoured by the NO presence Ti =350, T_{max}= 380,T_f =400 ^{0}C.
140	CO-Ba-K. Nitrate salts Impregnation.	TGA Soot/cat=1/3, Tight contact	Heated at 10 ^{0}C/min in air.	KNO_3 improves dispel-rsion of CO_3O_4 and $Ba(NO_3)_2$, the soot oxidn rate is greatly quickened Ti =343,$T_{50\%}$= 450 ^{0}C .
141	Co-Sr-K, Nitrate salts Impregnation	TGA Soot/cat=1/3, Tight contact	Heated at 10 ^{0}C/min in air.	Ti =300,T_{max}= 386. KNO_3 into Co-Sr catalysts greatly lower soot oxidation temp.
142	MoO_3,Co_3O_4-K_2O-Al_2O_3. $CoCl_2.6H_2O$,KNO_3, MoO_3. Co-impregnation.	TGA. Soot/cat=5/95, Tight contact	Heated at 5 ^{0}C/min in air	5 mol%MoO_3-10 mol% Co_3O_4-2 mol%K_2O-Al_2O_3 excellent catalyst Ti=190,T_f=410 ^{0}C
143	Ru & Co-ZrO_2 $RuCl_3$, cobalt acetate co-impregnation.	TGA Soot/cat=5/95, Loose contact	Heated at 5 ^{0}C/min in air	Ru(5 mol%)-Co(1 mol%) bimetallic clusters Ti = 310, $T_{50\%}$= 460, T_f =510 ^{0} C.
144	RuO_2–TiO_2 $RuCl_3$-TiO_2 Impregnation	TGA Soot/cat=5/95, Loose contact.	Heated at 5 ^{0}C/min in air	5.0 mol% RuO_2-TiO shows better thermal stability. TiO_2 good catalytic activity Ti =340, $T_{50\%}$= 440,T_f =550 ^{0}C.
145	Ag-Ce, Nitrate salts, Impregnation	TGA Soot/cat=1/80, Tight contact.	Heated at 5 ^{0}C/min in 20% O_2 -N_2 100cm^3 /min.	(Ag20Ce), > CeO_2, and the catalyst showed high durability. T_{max}=308 ^{0}C.
146	$SrTiO_3$, Wet Impregn ,Nitrate salts	TPD Soot/cat=1/10, Tight contact	Heated at 5 ^{0}C/min in air.	$SrTiO_3$ < Li/$SrTiO_3$ < Cs/$SrTiO_3$ < K/$SrTiO_3$. $Sr_{0.8}Cs_{0.2}TiO_3$=325 ^{0}C
147	KNO_3, KOH support on Zirconia, Impregnation	Fixd bed reactor Soot/cat=1/20,	Heated at 2 ^{0}C/ min in air.8% O_2-1500 ppm NO	KNO_3(5)/ZrO_2 shows best catalytic activity, Tmax=415 ^{0}C.
148	Cu/Mn-Ce Nitrate salts. citric acid sol–gel	TPO Soot/cat =1/10, tight & loose contact 110 mg	Heated at 10 ^{0}C/min.10% O_2 in N_2 500 ml/min.	Mn form solid solution, Cu & Ce release lattice oxygen of the oxides. Ti =338, T_{max}= 356,T_f =375 ^{0}C.
149	Cu–Ce–Al Nitrate salts. Citric acid sol–gel	TPR Soot/cat =1/10, tight & loose contact	Heated at 20 ^{0}C/ min, 1150 ppmNO 9.6% O_2-N_2 500 ml/min.	Cu–Ce–Al mixed oxide catalyst exhibits the maximum soot oxidation. T_{max}= 380^{0}C.
150	Ce–Al Nitrate salts. Citric-acid complexation-combustion	TPO Soot/cat =1/10 Tight contact	Heated at 1.3 ^{0}C/ min, flow rate of air 60 ml/min.	Al_2O_3 improves thermal stability of CeO_2 Highest soot combust-ion activity with T_{max} = 356
151	CeO_2, Ce-Zr, Cu-Ce , Ce/Zr=5/4 &Cu/(Cu + Ce + Zr)= 1/10. Nitrate salts, citric acid sol–gel.	TPO Soot/cat =1/10, tight & loose contact. 110mg.	Heated at 20 ^{0}C/min.1000 ppm NO+9.5 % O_2 - N_2 flow 500 ml/min.	Cu-Ce best catalyst for tight contact. NO facilitates for oxidation. Ti =300, T_{max}= 312, T_f =350 ^{0}C.
152	CeO_2-ZrO_2 (La, Pr, Sm, Tb, Fe), Nitrate Salts. Co-precipitation.	TGA soot/cat =1/115, Tight contact	Heated at 10 ^{0}C/min, air flow 100 ml/min	ZrO_2 is important to stabilize, Fe-doped active, Ti =330, T_{max}= 366, T_f =450^0 C
153	CeO_2, ZrO_2, Nitrate salts Co-precipitation	TPO soot/cat =1/10, tight & loose contacts	Heated at 10 ^{0}C/ min, 10% O_2 in N_2 flow 500 ml/min.	Ti =370, T_{max}= 375, T_f =450^0 C. K/$Ce_{0.5}Zr_{0.5}O_2$, thermally stable support
154	Co_3O_4–CeO_2 , Acetate of Co–Ce. Co-precipitation	TPO soot/cat =5/95, Tight contact.	Heated at 5 ^{0}C/min in air	20 mol% Co_3O_4-CeO_2 excellent catalyst, Ti =350, Tmax= 470,T_f=550 ^{0}C.
155	$SrCoO_3$, Nitrate salts Co-precipitation method	TGA Loose contact.	Heated at 5 ^{0}C/min in air	$Sr_{0.8}Ce_{0.2}CoO_3$, excellent catalyst, despite low surface area Ti =241, $T_{50\%}$= 420,T_f =500^0 C.
156	TiO_2, ZrO_2, CeO_2. Nitrate salts. Precipitation.	Fixed-bed soot/cat=1/4, Loose contact SiC diluent	Heated at 10 ^{0}C/ min 0.05% NO_x + 5% O_2 + N_2 flow 500 ml/min	TiO_2 & ZrO_2 - CeO_2- Ti=525,T50%= 551, T_f =625 ^{0}C.
46	$Ce_xZr_{1-x}O_2$, Nitrate salts Co-precipitation	TPO soot/cat =1/10, Loose contact.	Heated at 10 ^{0}C/ min. 10% O_2/N_2 flow 500 ml/m.	$Ce_{0.5}Zr_{0.5}O_2$ best catalyst Ti =410, T_{max}= 525, T_f =550^0 C.

catalytically coated traps for diesel soot removal [24]. Various catalyst systems based on transition metal oxides/salts such as Co-Ni [114], Cu-Fe [115], K-Cu, K-Co [116], Co-Ba–K [117], Cu-K-Mo [118], Cu-V-K [119], Cs–Fe–V [120] and other vanadate-based catalysts [121] have been studied and demonstrated the promise for diesel exhaust treatment. The catalysts based on rare earth metal oxides such as Ce–La [122], La–Cr [123], Pr–Cr [124], La–K [125], La–K–Cr [126], La–K–Mn–O [127], La–K–Cu–V [128] and Co–Ce [129] have also been widely investigated. All these catalysts exhibit a soot ignition temperature of about 350 ^{0}C and show a good catalytic performance for soot oxidation.

Watabe et al. [130] was the first to report a catalyst based on a formulation of Cu/K/M/(Cl), where M is V, Mo, or Nb. For years, catalysts based on this formulation were investigated extensively [118,131] because they exhibited high soot-oxidation rates at low temperatures. The high activity was related to the mobility and volatility of the active copper chloride component of the catalyst [132]. Unfortunately, catalyst compounds evaporated during soot oxidation [133], because of which the catalyst should be kept below 350 ^{0}C at all times, which makes the feasibility of the catalyst questionable [118].

Various alternatives for the Cu/K/M/(Cl) catalyst have been investigated. What they have in common is that the mobility of the catalytic phase played a major part in the oxidation mechanism. This mobility probably explains why the stability of some of the reported catalysts was low. Querini et al. [134] stated that the high activity of Co/MgO and Co/K/MgO could be caused by enhanced catalyst mobility caused by potassium. Badini et al. [135] reported that KCl : KVO_3 and KI:KVO_3 are active catalysts, but they also reported the emission of volatile components of the catalyst. Ahlström and Odenbrand [136] reported mobile catalysts that did not evaporate during soot oxidation.

Most Recently, Li et al. [157] prepared Fe-substituted nanometric perovsite-type catalyst ($La_{0.9}K_{0.1}Co_{1-x}Fe_xO_{3-\delta}$) showing highest activity at x= 0.1 for simultaneous NOx–soot removal, over which the maximal soot oxidation rate is achieved at only 362 ^{0}C (Tm), the NOx storage capacity reaches 213μmol g^{-1}, and the percentage for NOx reduction by soot is 12.5%. A list of representative recent literature on catalytic oxidation of soot in a well conceivable tabular form is provided in Table 3'

6. Conclusions

The Diesel engine provides great benefits to society, but recent attention has focused on the potential health effects of DPM and NOx. The VOF part of this DPM can be removed with very high efficiency using a diesel oxidation catalyst. However, these flow-through catalysts do not convert the carbonaceous core of the DPM. The DPM can be almost completely removed from the exhaust stream using a DPF. This trapped DPM can then be combusted using either NO_2 (at low temperatures, 250–300 ^{0}C and above), or O_2 (at high temperatures, 550–600 ^{0}C). The NO_2-based regeneration process can be implemented passively on current HDD vehicles, as exemplified by the CRT system. Sophisticated engine management strategies, combined with catalytic processes, are used to raise the temperature of the DPM collected in the DPF to the temperature required for the O_2-soot oxidation. The accumulated carbon is then rapidly burned away. In conclusion, the technology to control the DPM emissions from Diesel vehicles has been successfully developed and demonstrated, and many vehicles in use today benefit from the application of these catalyst based DPM control strategies.

All of the improvements in controlling automotive exhaust emissions depend on catalysis, and the most recent on-road measurements show that appropriately designed catalytic systems are capable of effectively eliminating not only the DPM but also NO_x. Thus the application of catalytic systems to control the emissions from diesel engines of all types continues to improve urban air quality. Clearly, reduction of soot and NO_x emissions will have a major positive impact at the local level (reducing fatalities); at the regional level (avoiding potential negative impacts on monsoon and glaciers that feed rivers like Ganges and Brahmaputra in India); and at the global level (reduction of global warming).

List of Abbreviations

ABCs =Atmospheric brown clouds
CRT =Continuously Regenerating Trap
DOCs=Diesel oxidation catalysts
DPF=Diesel particulate filter
DPM= Diesel particulate matter
EPA= Environmental protection agency
FBC=Fuel borne catalyst
HC =Hydrocarbons
HEI= Health Effects Institute
IARC= International Agency for Research on Cancer

NIOSH= National Institute for Occupational Safety and Health
PAH= Polycyclic aromatic hydrocarbon
PGM= Platinum group metals
TGA=Thermo-gravimetric analysis
TPD= Thermal programmed desorption
TPO=Temperature programmed oxidation
TPR= Temperature programmed reduction
VOC =Volatile organic compounds
VOF=Volatile organic fraction
WHO= World Health Organization

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