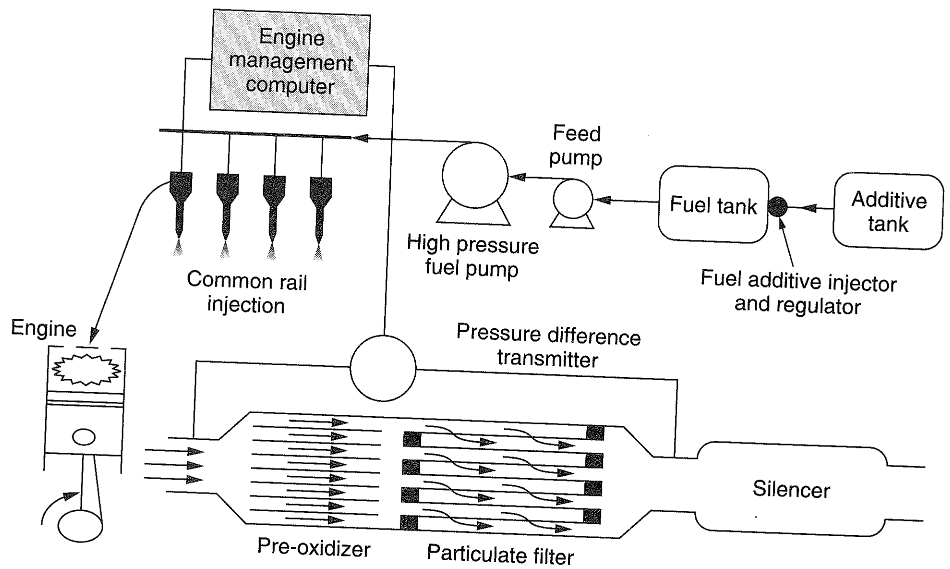

FIGURE 19.20 Schematic of PSA Peugeot Citroën system.

additive solution ensures a range of 80,000 km. After this 80,000 km the tank can be refilled and the filter cleaned with a water jet to remove the cerium and lubricant ash deposits. For the new type of diesel engine with less soot emission, Rhodia has developed a new type of additive based on cerium and iron [84]. The claimed advantages are that a lower additive dosage rate of only 10 ppm can be used, the regeneration starts at a temperature of around 375°C, and the time needed for regeneration is much shorter. As a result the system is more fuel efficient and the redesigned (larger) filter has only to be cleaned after 300,000 km (probably the lifetime of the engine).

19.7.2 Continuously Regenerated Trap

The NO_x-aided continuously regenerated trap (NO_x-aided CRT) for trucks and buses was developed by Cooper and Thoss [54]. It consists of a wall-flow monolith with an upstream flow-through diesel oxidation catalyst, which is called, in this context, the preoxidizer. Figure 19.21 shows a schematic of the system. The oxidation catalyst converts 90% of the CO and hydrocarbons present to CO_2 and H_2O, and 20 to 50% of the NO to NO_2 [84]. Downstream, the particles are trapped on a cordierite wall-flow monolith and, subsequently, oxidized by NO_2.

The modular design of the separated and detachable preoxidizer and filter provide flexibility to the system, which is a great advantage for retrofitting different buses and trucks. In each case, the optimal trap and preoxidizer can be chosen, which in many cases saves space, heat loss, back-pressure, and system costs.

The filter should produce a surplus of NO_2 in order to compensate for time intervals 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 sufficiently diluted with ambient air. For the environment, compared with NO, NO_2 gives no additional problems, because NO converts to NO_2 anyway on short timescales [85].

The NO_x-aided CRT system, as illustrated in Figure 19.21, is an effective catalytic filter that oxidizes all carbon components in diesel exhaust gas, including small particles and unregulated compounds, while reducing the NO_x concentration by 3 to 8% [86]. It is a simple

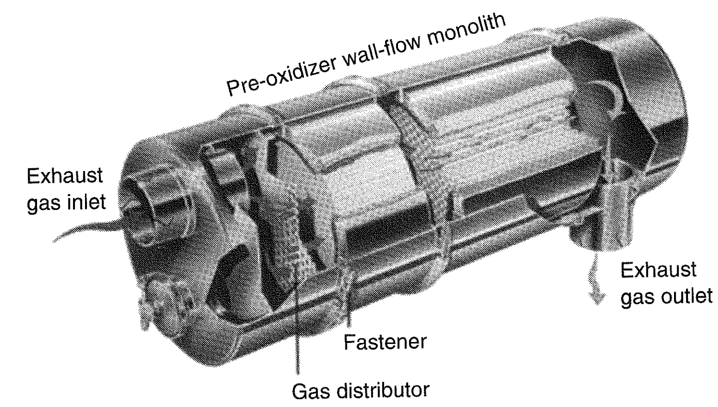

FIGURE 19.21 Continuously regenerating trap (CRT) system. (Courtesy of Johnson Matthey.)

concept that allows for fit-and-forget usage. The temperature window of 200 to 450°C is reasonable; 200°C is needed for CO and hydrocarbon oxidation [86], whereas 450°C relates to the chemical equilibrium between NO and NO_2, which is not favorable above 450°C. The temperature in the filter should be higher than 425°C for at least 40% of the time for effective filter regeneration. The balance temperature is actually higher than 425°C and depends on the fuel sulfur level. The maximum acceptable sulfur level is 30 ppm. Due to continuous regeneration, extreme temperatures are avoided, which enhances filter durability. A satisfactory performance for up to 600,000 km [86] has been reported.

Since the system depends on NO_x, it will be uncertain if the required NO_x-to-soot ratio for successful regeneration will be met in future engines. One option for less dependency on engine-out NO_x is the multiple usage of available NO_x. Therefore, a study to optimize the oxidation of NO to NO_2 and the oxidation of soot was carried out. Coating the filter section with platinum to reoxidize NO produced from reactions (19.2) and (19.3) is the latest effort to optimize the system [87].

19.7.3 Combined Continuously Regenerated Trap and Catalytically Regenerated Trap

"Active Oxygen" is postulated as a species that plays a role in the newly developed system, the diesel particulate and NO_x reduction (DPNR) Toyota Motors system [88,89]. In the DPNR system a layer of an "active oxygen" storage alkali metal oxide is deposited along diesel soot filtration surface areas. On this layer platinum is dispersed. The "active oxygen" is created by the conversion of gas-phase NO over the platinum into surface nitrate species. These surface nitrates will be decomposed at the interface between the soot and active oxygen layer into very reactive adsorbed oxygen atom and NO. The NO can be reoxidized to surface nitrate and the adsorbed oxygen atom is able to oxidize the deposited soot at 300°C and higher. If the system is not able to convert all deposited soot the back pressure over the filter will increase and trigger the regeneration of trapped soot due to a temperature rise in the filter. This increase in temperature is accomplished by injecting diesel fuel directly in the exhaust stream.

The active oxygen storage material acts at the same time as a NO_x trap. When the NO_x trap has reached its maximal allowable buffer capacity for retaining all NO_x as nitrates, then the NO_x trap needs to be regenerated. CO and HCs can decompose these nitrates into nitrogen. These CO and HCs are generated by running the engine rich or by fuel addition

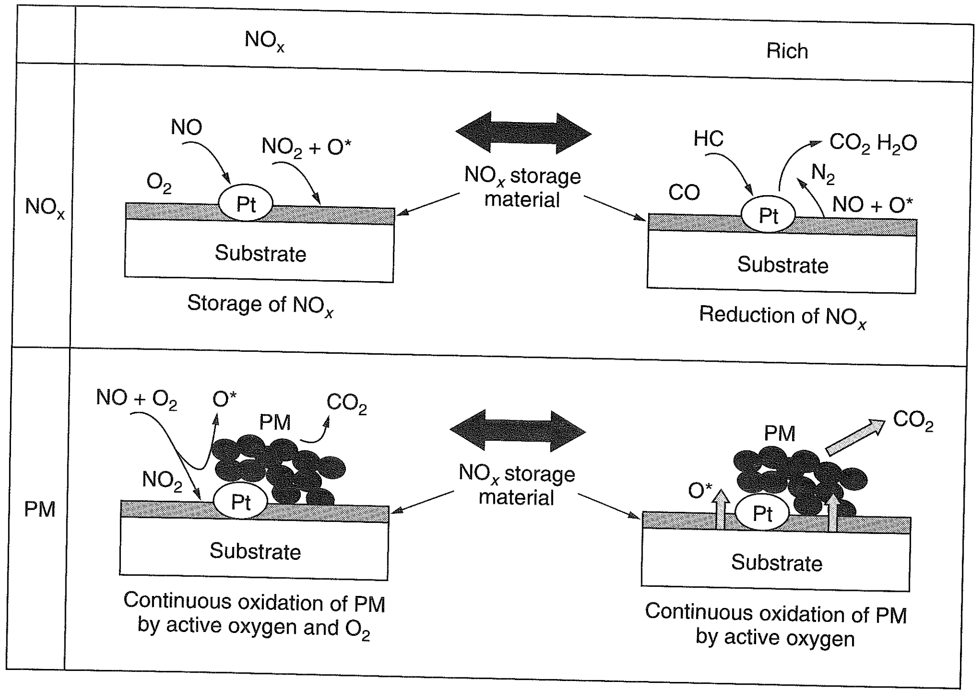

FIGURE 19.22 Schematic of the diesel particulate and NO_x reduction (DPNR) Toyota Motors system.

into the exhaust stream at a temperature of around 450°C. The newly generated CO and HCs are converted into CO_2 by surface nitrates while the nitrates themselves convert mainly to N_2 and, to some extent, to NO. In other words, this type of soot oxidation trap acts as a soot abatement technology, while at the same time it acts as a NO_x abatement technology. Figure 19.22 illustrates the chemical processes of the Toyota system.

Total reduction of diesel exhaust emissions (CO, HCs, PM, and NO_x) is preferably achieved in a single filter system such as the DPNR system. However, this system may encounter several problems such as engine ash deposit, complexity of data logging, and the effectiveness of engine-out NO_x concentration. It is reported that the fresh DPNR system reduces 80% of NO_x and PM emissions and might meet the U.S. tier 2 bin 5 or 6 emissions standards using low-sulfur diesel fuel [90]. It is evident that a fleet test has to demonstrate the efficiency and robustness of the system.

19.8 SUMMARY

The stringent emissions legislation for diesel-powered vehicles has led to new developments in both oxidation catalysts and filters. These developments include new materials for catalyst supports and filters with higher heat capacity, filtration area, and physical durability. In addition, the advent of low-sulfur fuels is helping in developing catalysts to meet the 300,000 km vehicle durability. Similarly, improvements in engine design have reduced particulate matter via more efficient fuel combustion. Furthermore, significant progress is being made in reducing oxides of nitrogen via NO_x adsorbers and DeNOx catalysts. Also, a variety of fuel additives have been developed that help reduce the soot regeneration temperature thereby reducing thermal stresses and enhancing physical durability of diesel filters. Twenty-five years of successful experience with ceramic catalyst supports for

automotive application is proving valuable in designing robust mounting system for diesel oxidation catalysts. In view of considerably lower operating temperature and longer physical durability requirement, relative to automotive catalysts, the intumescent mat used in packaging diesel oxidation catalysts has to be preheated to ensure sufficient holding pressure on the catalyst against inertia, vibration, and road shock loads experienced in service.

Filter materials having a higher melting temperature than cordierite have also been developed and are being used in commercial applications subject to more stringent emissions legislation. These include SiC and RC 200/19, which are able to withstand uncontrolled regeneration due to either their higher conductivity (SiC) or heat capacity (RC 200/19). SiC offers higher thermal conductivity and melting temperature, which are very desirable for uncontrolled soot regeneration, but its order of magnitude higher thermal expansion coefficient can lead to inferior thermal shock resistance [91]. An improved version, namely Si/SiC composite material, has recently been developed which offers low thermal expansion coefficient and superior thermal shock resistance.

Finally, the mounting system can play a major role in ensuring both mechanical and thermal durability of diesel oxidation catalysts and filters notably for heavy-duty trucks with severe operating conditions and 500,000 km vehicle durability requirement. Many of the robust packaging systems employed in automotive applications are equally applicable to both diesel oxidation catalysts and filters.

The successful introduction of the particulate filter system by PSA Peugeot Citroën and the continuous regeneration trap (CRT) by Johnson Matthey are the evidence of persistent and creative research. The catalytic advanced technology of Toyota with their DPNR system is another clear demonstration of high-standard reactor and catalysis engineering.

NOTATION

A_{open}	open cross-sectional area (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
C	constant in Equation (19.11)
d	diameter (m)
D_h	hydraulic diameter (m)
g	gravitational acceleration (m sec^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
l	length (m)
L	cell spacing (m)
n	dynamic fatigue constant
N	cell density (cells m^{-2})
Δp	pressure drop (Pa)
P	fractional porosity of filter wall
Q	flow rate through filter (m^3 sec^{-1})
S_1	safe allowable stress
S_2	filter's short-term modulus of rupture
t	wall thickness (m)
t_1	specified filter life (sec)
t_2	equivalent static time (sec)
T	temperature (K)
v	gas velocity (m sec^{-1})
V_f	filter volume (m^3)
α	coefficient of thermal expansion (K^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})

ρ	density ($kg\,m_f^{-3}$)
μ	gas viscosity ($kg\,m^{-1}\,sec^{-1}$)

Subscripts

c	center
ch	channel
en	entrance
ex	exit
p	peripheral, pore
s	soot
w	wall

Abbreviations

BPI	back-pressure index (m^{-1})
CTE	coefficient of thermal expansion (K^{-1})
MIF	mechanical integrity factor
MOE	modulus of elasticity (Pa)
MOR	modulus of rupture (Pa)
OFA	open frontal area
SFA	specific filtration area (m^{-1})
TFA	total filtration area (m^2)
TSP	thermal shock parameter (K)

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