Lecture 31:Diesel Particulate Filters (contd.)

The Lecture Contains:

- Passive/Catalytic Regeneration
- Regeneration by Fuel Additives
- Continuously Regenerating Trap (CRT) Syatem
- Partial Diesel Particulate Filters
- Summary of Diesel Engine Emission Control

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Continuously Regenerating Trap (CRT) System

The principle of CRT is based on the fact that NO_2 is a much superior oxidizing agent for soot than the molecular oxygen. $300°C$ oxidizes the dry carbon soot trapped in the filter below 300° C by the following reactions:

$$2NO_2 + C \rightarrow CO_2 + 2NO \qquad (6.11)$$

$$NO_2 + C \rightarrow CO + NO \qquad (6.12)$$

Although the trap substrate can be coated with a catalyst material to reduce soot oxidation temperatures to as low as 200° C, but installation of an oxidation catalyst upstream of particulate filter where NO is preferentially converted to NO_2 which then oxidizes the soot has been found more effective. The catalysts used are noble metals. The oxidation catalyst is a flow through ceramic monolith using Pt-Pd catalyst impregnated on Al_2O_3 washcoat.

The schematic of a CRT is shown in Fig. 6.18. NO_2 is produced by oxidation of NO upstream of DPF. The soot trapped in the downstream DPF is continuously oxidized on the filter substrate by NO_2 thus keeping the particulate filter essentially clean and the exhaust backpressure remains nearly unchanged.

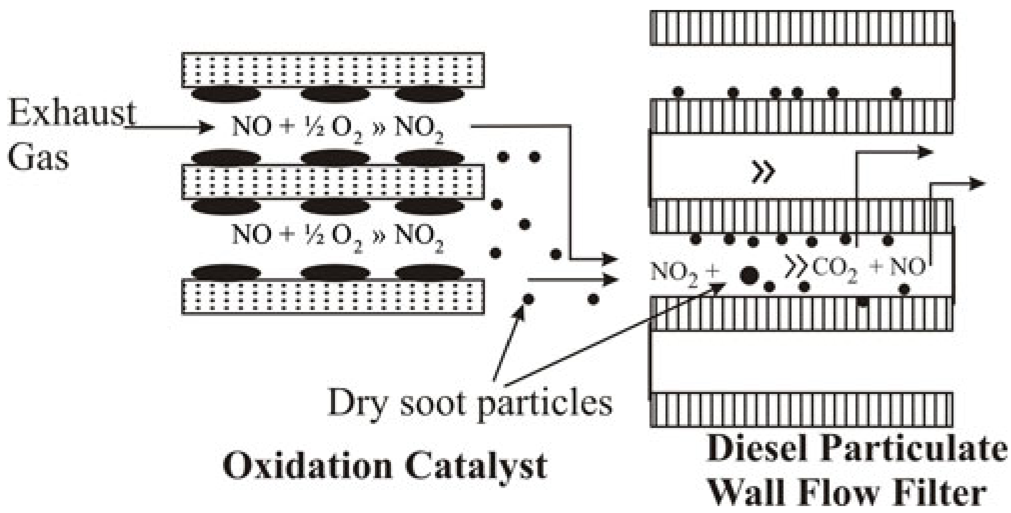

Figure 6.18	Schematic of a continuously regenerating trap (CRT).

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Passive/Catalytic Regeneration

The active regeneration systems need complex control systems and are expensive. The passive regeneration systems employ catalysts to reduce soot oxidation temperatures to the levels that lie within the normal exhaust gas temperature range. The catalyst is either added to diesel fuel in the form of additives or is impregnated on the surface of the filter substrate. Another approach for passive regeneration uses a special oxidation catalyst in front of the ceramic wall flow particulate filter to promote soot oxidation. This system is known as the continuously regenerating trap (CRT).

Regeneration by Fuel Additives

Several fuel additives based on Fe, Ce, Mn, Zn, Cu and Pb lower the soot oxidation temperature. Cerium and copper based additives in 60 to 100 ppm concentration have been found very effective in lowering soot ignition temperature to about 300º C and soot regeneration has been achieved at temperatures below 400º C. The additives on oxidation produce metal oxides which promote oxidation of soot. For example, cerium fuel additive is converted to cerium oxide on combustion and on reaching the DPF it catalyses soot oxidation. The oxidation mechanism is as below;

1. Oxidation of soot:

$$2CeO_2 + C \rightarrow Ce_2O_3 + CO \qquad (6.8)$$

2. Oxidation of CO

$$CO + {}^{1}/_{2}\, O_2 \rightarrow CO_2 \qquad (6.9)$$

3. Ce_2O_3 being an unstable compound gets converted back to CeO_2 in the exhaust gas as excess oxygen is available

$$Ce_2O_3 + {}^{1}/_{2}\, O_2 \rightarrow 2CeO_2 \qquad (6.10)$$

These reactions are quite fast and are completed within 2 to 6 seconds once the temperature is sufficiently high. The fuel additive based approach for particulate trap regeneration is considered quite promising. The additive can be dosed into the fuel line when required by automatic dosing equipment on board of the vehicle.

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Fuel sulphur is an important factor that affects conversion of NO to NO_2 on the oxidation catalyst and hence the efficiency of CRT. Fuel sulphur lower than 30-ppm has been found necessary to maintain the functioning of CRT at an acceptable level. In Europe, where low sulphur fuel is available several thousand vehicles with CRT are in operation. To achieve the best performance of CRT, the following conditions should be met:

- Sulphur-free fuel (sulphur <30ppm) is necessary to prevent catalyst poisoning
- For best performance temperature should be in the range 250 – 450º C.
- The NO_x/ soot ratio should be adequately high otherwise NO_2 available will be too low to oxidize soot.

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Partial Diesel Particulate Filters

Although wall flow diesel particulate filters have very high particulate trapping efficiency, but their regeneration over the entire life span extending up to 496,000 kms for heavy duty vehicles is a challenging problem. In Europe, many diesel vehicles meeting Euro 4 standards are fitted with 'wall flow' particulate filters as original equipment. Metal supported flow- through diesel filters employing CRT operational principle have also been developed recently These filters have been developed to provide 50 to 70 percent reduction in PM emissions and therefore, are called as 'Partial Particulate Filters'. Like CRT, upstream in the first section an oxidation catalyst is installed where NO is oxidized to NO_2. In the second section, which consists of flow-through type filter element collection of soot and its combustion processes occur.

.A schematic cut-away section and working principle of the filter is shown on Fig. 6.19. The metal PM filter consists of flat and corrugated foils in a flow-through monolithic configuration. The corrugated foils are stamped to produce blades like structure to direct the flow towards the flat foil. The flat foil is made of porous sintered metal fleece (wool) packed in the form of a sheet and compressed between metal foils. Part of the exhaust gas is directed by the blades in the corrugated foil towards the porous metal wool that traps the particulate matter. The soot trapped by the metal wool is oxidized by NO_2 generated on the catalyst in the upstream first section. The design of this diesel particulate filter has open channels and it does not get clogged due to excessive accumulation of soot as happens in the 'wall flow' filters on failure of regeneration. All the exhaust is able to flow through the open channels if the metal fleece is choked. However, in such a situation removal of PM from exhaust does not take place. Typical cell density of these filters is 200 cpsi. With use of these particulate filters reduction in PM emissions ranging from 30 to over 70 % have been obtained.

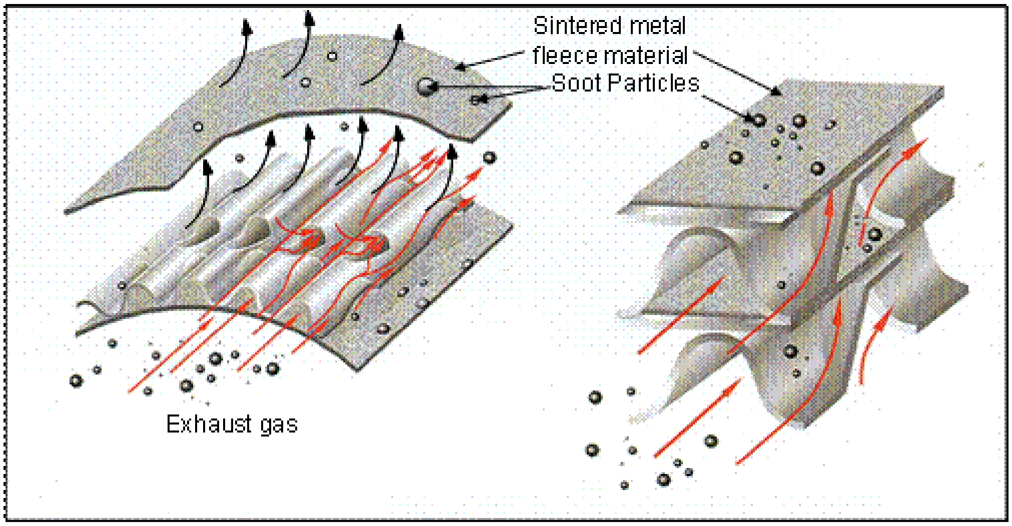

Figure 6.19	Working principle of metal supported partial PM filter-Catalyst

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Summary of Diesel Engine Emission Control

Developments in diesel engine emission control technology that have taken place over several decades are summarized in Fig. 6.20. The developments have been directed towards advancements in technology to control;

- Engine out emissions and
- Exhaust after treatment

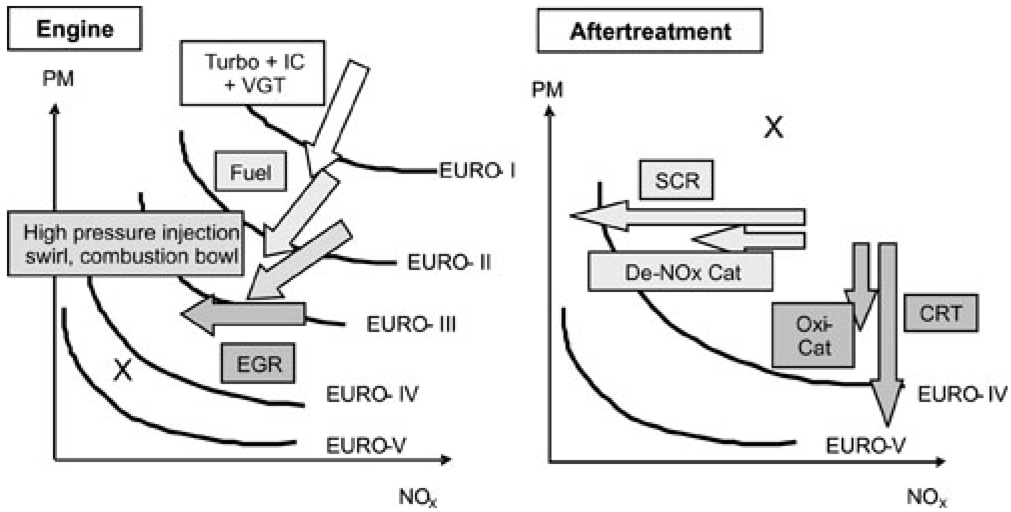

Figure 6.20	Summary of advancements in diesel emission control technology.

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Summary of advancements in diesel emission control technology.

As seen from the Fig 6.20, the engine technologies have been able to reduce emissions to Euro IV emission levels. The technologies employed progressively included;

- Turbocharging with inter-cooling
- Variable geometry turbocharging
- Improved fuels esp. low sulphur in addition to low final boiling point and closer control on density, viscosity etc.
- High injection pressures
- Optimization of combustion bowl geometry and air motion
- EGR

Aftertreatment Technology for Euro V and beyond:

The second stage is the exhaust after treatment. In some engine models even to meet Euro IV standards diesel oxidation catalysts and SCR de-NOx catalysts were employed. However, for Euro V and later standards some form of exhaust treatment is almost essential. Most engines would employ:

- Diesel particulate filters: DPF or CRT
- de -NOx catalysts: SCR or other types

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Questions

(6.1) A diesel engine is fitted with mechanical injection pump with 60MPa peak injection pressure. Another engine of the same size developing the same power is employing common rail injection system with 160 MPa injection pressure. Both the engines operate at the same rated speed. Discus the likely differences between the two engines with respect to (i) injection duration (ii) nozzle hole size (iii) atomization and droplet size (iv) injection timing (v) fuel evaporation , mixing (vi) ignition delay and premixed combustion (vii) over all combustion rates (vi) PM and NOx emissions.

(6.2) Calculate stoichiometric NH_3/ NO_x ratio for reduction of NO_x in SCR catalysts if the entire NO_x is only NO, and consists of 5 and 10% NO_2 by volume. If 20 % more NH_3 than stoichiometric requirements is supplied calculate ammonia slip in ppm if the NO_x concentration in the exhaust gas before conversion was 2000 ppm.

(6.3) A diesel particulate filter (DPF) fitted to a 12 litre DI diesel engine is to be regenerated. The engine has volumetric efficiency of 88%, is operating at 67 % excess air and 2000 rpm. The ambient air conditions are 101 kPa and 300 K. For burning the soot collected on the DPF, the exhaust gas temperature is to be raised to 540º C. The exhaust gas temperature entering the DPF is 350º C. Determine the power of an electric heater to raise the exhaust gas temperature to the required level if the entire exhaust gas is to be heated. The specific heat of the gases in the relevant temperature range is N_2 = 30.27, CO_2 = 46.56, O_2 = 31.96, 36.44 kJ/kmol. K.

(6.4) Given the LHV of soot = 33.8 MJ/kg , if in a DPF of 1 litre volume 10 g of soot is burned estimate the temperature reached in the DPF. The combustion of soot begins at 540º C. The mass of the DPF is 400 g and its specific heat is 0.9 kJ/kg.K.

(6.5) Refer Fig 6.20. Discuss how various technologies have helped in reduction of engine out emissions from the diesel engines.

(6.6) A diesel engine has BSFC = 240 g/kWh. In the engine cylinder, lubricating oil enters through piston rings and valve guides which amounts to 0.2 % by mass of the fuel consumption. Of the engine oil in the cylinder, 80% is burned and rest is exhausted as SOF of particulate emissions. Estimate the specific PM emissions solely contributed by the engine oil. How do these compare with the Euro IV PM emission limits for heavy duty engines?

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