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A Report on
Current Trends of Emission Reduction Technology in Vehicular Diesel Engines

Abstract :

Combustion is the primary source of vehicular pollution,[1]. The Euro countries recently agreed on the goal that would reduce current vehicular emission , in particular carbon emissions by 85% by 2050. This would mean a 95% reduction in the carbonisation of the transportation sector, which is one of the accepted prolific contributors to pollution,[10]. As will be seen, de-carbonisation is a key issue with vehicular light duty diesel engine emissions,[9],along with reduction in $NO_{x,}$ with the latter being highlighted[3,4]. Two constituents of diesel emissions, Particulate Matter (PM) and NO_x are contradictory in the conditions of their formation and hence require a combination of technologies to solve the problem satisfactorily. Consequently, emission reduction technologies are

The most stringent norms are those of Super Ultra Low Emission Vehicles (SULEV) formed by the Environmental Protection Agency (EPA) and the Euro 6 has been proposed and awaiting approval. The author's opinion of a balanced solution being a combination of several technologies is established. The logical path to this conclusion is presented, duly referenced.

Introduction :

Classification and Overview:

For convenience, in this report emission reduction techniques are split into primarily a) '*Primary Engine Developments'(PED)*, which refer to more efficient or rather customised , (Lean/rich/stoichiometric) engine technology as per the application under which aspects like fuel injectors, combustion chamber and valve geometry, configuration and ignition timings etc come into the picture (b) '*Secondary Engine Developments' (SED*), which includes technology processing/filtering the exhaust coming out of the engine or utilising its energy contents and thus increasing the power and efficiency, like and Exhaust Gas Recirculation (EGR), Diesel Particulate Filters(DPF), Diesel Oxidation Catalysts (DOC) and Turbochargers respectively. Current vehicles use a combination of these technologies to meet emission norms. The effect and range of PED and SED are shown in a convenient representation found in [4] .

A chronological and quite progressive account of the progress of in the control of Light Duty Diesel (LDD) emission standards legislations with respect to diesel tail pipe emissions can be found in [2-4]. If De-Carbonisaton seems too far away to worry about, a striking point to note is that the proposed (for 2014) Euro 6 norms require over 85% reduction in NO_x emissions to compete with the stringent standards of SULEV, [4], see figure 5. Though these norms are here for a reference, or goal, the ideal objective is to have zero emissions, and understand the source, combustion, which is why PED is as important as SED in emission reduction.

'The real picture'? :

Combustion is quite a complicated process, especially with it happening in an enclosed volume and is kept going by a complicated mechanical system with probably hydraulic and electronic components and systems involved to ever increasing extents. It is very difficult to view the process inside the chamber and finally, studies are carried out in simple bombs, like in the University of Leeds into which windows are drilled in to view the chamber with high speed photography and advanced techniques like Schlieren photography and etc.These experimental setups are not as close to reality as one would like. Injection frequencies in diesels could range around 2000 times a second. The injectors are thus, extremely important in a diesel engine. Then comes, combustion behaviour. These are the reasons that PED was initially slow. Several fundamental questions of the behaviour of turbulence and flame propagation exist, currently outside analytical reach. So, numerical and empirical solutions are used to discretise the governing equations over the required geometry, within a computational domain with approximated scales for the particle sizes. The constituents of the final exhaust emission are obviously, deeply linked to the combustion process and thus, its products. This probably explains the logical, sudden and intense focus on relatively simpler vehicle exhaust after treatment technology, and it's success in terms of manufacturers meeting emission norms and being able to increase the cost of their new environmental friendly vehicle.

Discussions:

PED:

Technological, and computing development and simulation techniques like Computational Fluid Dynamics (CFD) have enabled a better knowledge of flame propagation, nozzle and fuel injector behaviour, chamber geometry and fluid mixing characteristics, the last being a weighty issue in diesel engine technology, and which is interestingly also the principal 'purpose' of turbulence, [1,7,]. It is an interesting point to note that a fuel injector system in a diesel engine costs as much as an entire Spark Ignition (SI) engine, [1]. Several motions can be induced in the chamber through geometry variation and injector orientation. The mixing of fuel and air is the most important part of the Compression Ignition(CI) type engine. Consequently, swirl , squish and turbulence are essential characteristics of the mixture motion in the chamber. Swirl can be visualised as a whirlpool around an axis at which the velocity of the fluid is zero. It is inversely proportional

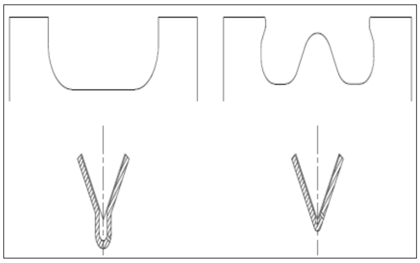

Figure 4 The left is the baseline model and the right is the improved chamber and injector geometry, [7].

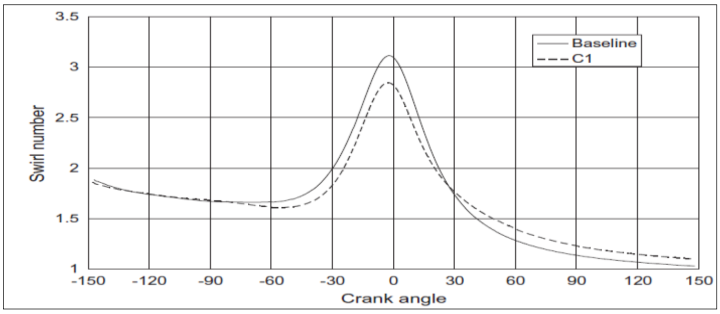

Figure 3 Variation of Swirl number for the two geometries shown in figure 2,[7].

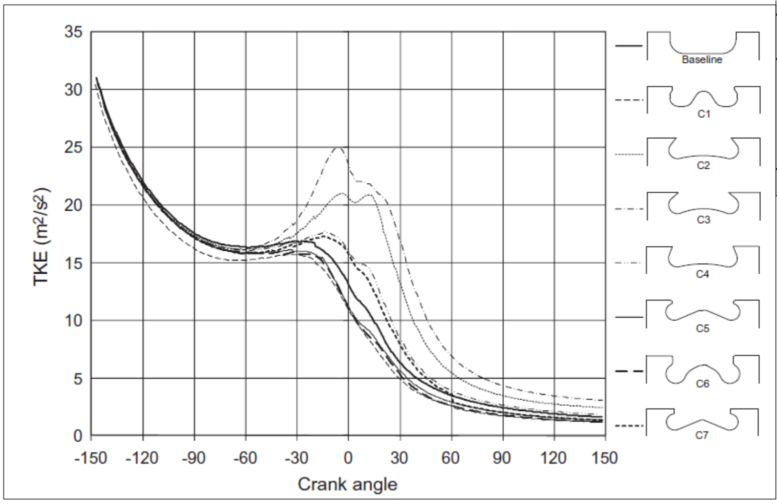

Figure 2 Variation of the Turbulent Kinetic Energy (TKE) with the crank angle and valve movement, for different chamber configurations [7].

	Injection timing (w.r.t. TDC)	NO_X (g/(kW h))	Soot (g/(kW h))
C3I2	−15.6	18.66	0.06
C2I2	−15.6	17.49	0.05
C7I2	−15.6	10.06	2.54

Figure 1 Change in emission levels with injection timing for the different configurations. $C_{3|2}$ refers to a model with the 2nd optimised injector in figure 3,[7]

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to the radius, moving outward. Squish relates to a layer or chunk of the whirlpool being compressed.

The reduction of PM emission to be a function of improved injectors and better mixing strategies is shown in [7]. The fuel injector geometry having little effect on the swirl number and Turbulent Kinetic Energy (TKE) where the swirl number is the ratio of the swirl speed to the engine speed, is a remarkable point to note, see figure 3,1. The slight reduction in peak swirl and alteration in turbulence intensification values at the Top Dead Centre (TDC) of the piston, is attributed to an more (13%) surface area caused by the projection, and thus increased skin friction/drag. As shown in [7], these motions essentially form two counter rotating vortices, each in the two curved areas of the torroidal chamber, due the squish and swirl competing against each other resulting in flame stretch. The various geometries by the author are shown in figure 4 on the right side with the optimum selection being C3.

It is however important to note that optimising the swirl, increased the NO_x while decreasing the PM by reducing ignition delay and causing, more efficient combustion with higher pressures and turbulent kinetic energy, and therefore higher temperatures. The ideal conditions of NO_x formation are those facilitating PM reduction, as stated before.

The optimised model enabled better mixing, displaying lower equivalence ratios than the baseline model. The equivalence ratio is measure similar to the density by volume of the fuel with respect to the entire volume.

It is interesting to observe that the trade off between NO_x and soot formation was finally achieved by varying the injection timing (advancing). The effect of a multi-holed(nos : 6) nozzle, with the same amount of fuel and thus smaller nozzle diameters, was also studied and was found to reasonably produce the same emission results on a lower scale of magnitude and hence the injection timing had dominance.

The reduction of NO_x using swirl by using inducing a very high speed swirl and thus cooling the flow is explored in [10], but produces very low emission reductions. However, it has been shown to facilitate fumigation and the mixing of *hybrid* diesel engines bringing about 50-60% reduction in PM,[11], which, given the energy crisis will inevitably become popular.

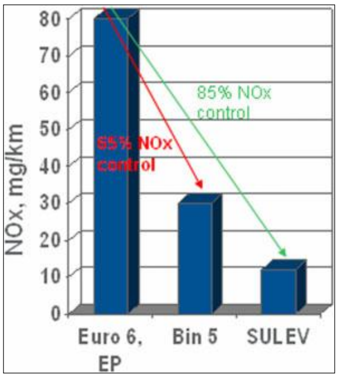

Figure 5 Comparison of Norms for NOx emissions,[4]

Note :

It is clear from many sources,[1-10] how the issue is further complicated in diesel engines by a trade off required between NO_x and PM, with their contradictory formation conditions coupled with stringent norms for NOx coming up, see figure 5. Considering that mechanical efficiency and inertial and viscous losses can never be zero, SED techniques are more successful in the control of NOx.

SED:

The excess oxygen produced in Lean Burn (lower fuel : air) engines, with high temperatures lead to excessive NOx formation. Rich mixtures are application dependent. However, consumer demand for powerful vehicles leads to the requirement of an adaptive solution for lean-rich mixtures. Besides, to cope with legislations, after exhaust treatment is required over and above advances in PED and EGR. This report focuses on the effects of a combined SCR+LNT system in controlling NOx.

SCR's have been widely used in controlling NOx with a large degree of success,[4,5]. An SCR basically reduces NOx using a reductant in the presence of a catalyst to accelerate things. Its performance characteristics, effective operating temperature and efficiency, widely

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vary, depending on the reductant and catalyst used, [4] .Conventionally, Ammonia (NH3-SCR) has been used as a reducing agent ,extracted from Urea mixed in the exhaust. Hydrocarbons can also be used as a reductant (HC-SCR) and this method is relatively new and inexpensive and simpler but studies have shownt the amount of HC available to not be sufficient to enable efficient regeneration of the catalyst.

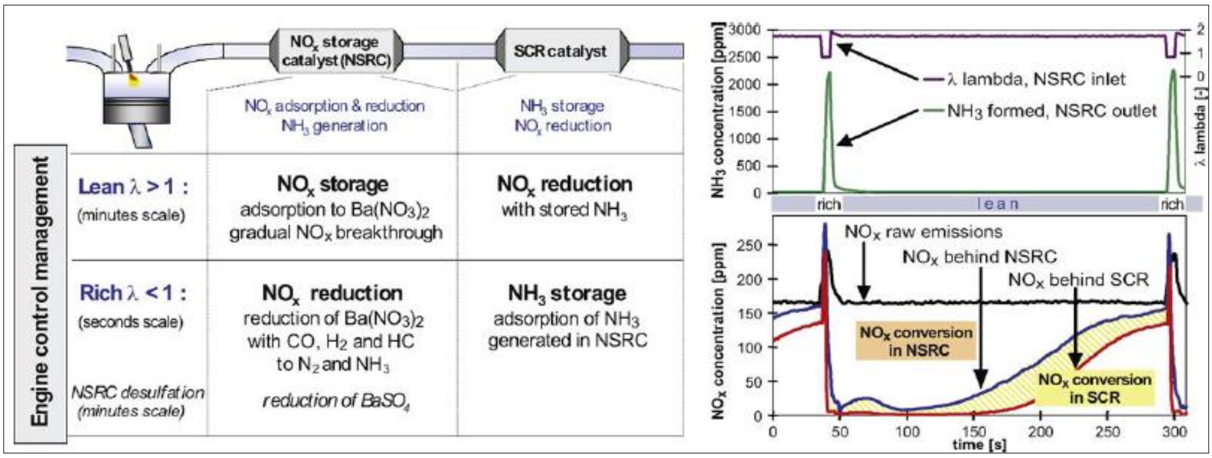

Figure 6 Principle of the combined exhaust gas after treatment system consisting of NOx storage & reduction catalyst (NSRC) and selective catalytic reduction of NOx by NH3 (SCR), [8]

In LNT's, the NOx is adsorbed onto the surface of a catalyst during the lean operation and is regenerated periodically by a pulse of increased reductant, obtained from the rich mixture. However, recent developments in LNT's , also called NOx Storage and Reduction Catalysts (NSRC) have reflected that high amounts of NH3 can be formed by varying the pulse length, temperature and gas composition,[8,12]. This ammonia is fed into the SCR to be used as a reductant. LNT offers several advantages in terms of the fixed cost of onboard storage and increased efficiency in the usage of the catalyst

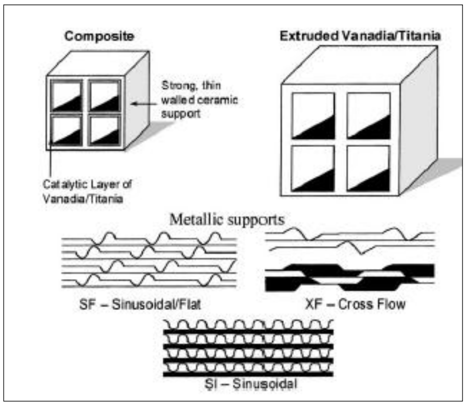

Figure 7 There are many techniques in which Catalysts are made as shown in the figure,[13].

Using either an SCR or LNT separately has a number of drawbacks, such as the Urea which has to be periodically refilled and the design allowances to be made for the storage and transmission of Urea, the high activation temperature of the catalyst , the cost of the catalyst. It should be also be noted that when SCR's are used in conjunction with other components like a DPF, they are subject to be imposed to higher temperatures and other varying conditions which must be accounted for.

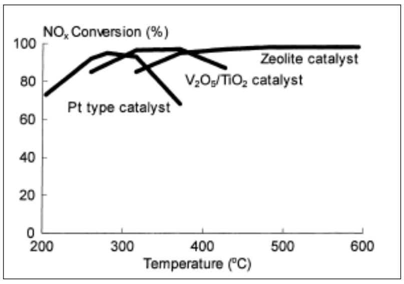

Figure 8 Comparison of the NOx conversion capabilities of the three main families of catalysts,[13].

The type of catalyst used is broadly dependent on the operating temperature range and the materials and manufacture costs and the important parameter of catalyst poisoning and its life. The main families of catalysts and their conversion capabitlities can be seen in figure 7. There has been a trend towards what is termed as Zeolitic metals being used as catalysts due to their lower cost. The copper zeolite combination has been widely used for its low temperature operation but water and sulphur poison the catalyst rather quickly, while Iron-(Fe)-Zeolites possess highest operating temperature capabilities. There are various ways of designing the catalyst and the flow through the substrates as shown in figure 8.

A combined system layout has been shown in figure 6, along with the NOx reduction characteristics of the system. The symbol Lambda refers to the air fuel ratio.It should be noted that the reduction efficiency of the combined system is around 96% with a slight optimisation in the pulse frequency and duration.

Conclusions :

From a fuel consumption point of view ,which has been somewhat missing in this report, it is been assumed that the cleanest vehicles have the highest fuel consumption, which could be an idealisation which is squared on acceptable grounds, that when the combustion is complete the exhaust is zero, with all the pollutants taken care of.

It is also worth mentioning that the trend towards smaller faster engines and the downsizing has resulted in almost 50% increase in NOx emissions in such engines. The Euro 6 norms, in addition to defining a Particulate Number, will probably have regulations for the emission of CO as well, which has not been covered in this report, considering that diesel's, have very low CO emissions and added to which the pulse duration of the LNT can be modified so as to have 100% removal of CO [12].

It has been shown that modifications in the frequency of the fuel injection can achieve similar results as introducing swirl as shown in this report. It would be interesting to combine such techniques together and discern their effect on the exhaust pollutants.

From the above, it is clear that a combination of PED's and SED's are required to achieve reduction in emission principally because no one method can remove all the pollutants. The complications involved in understanding and measuring emissions as a function of combustion. One must also consider the different testing cycles of the Euro and American regulation authorities. The above report is not exhaustive, but it is clear that adding an EGR system and a suitable DPF would only make the exhaust cleaner by recycling and filtering it further.

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Figures :

1-4: from [7]
6- from [8]
5 : from [4]
7,8 :from [13]