TRENDS IN AUTOMOTIVE DIESEL ENGINES' DESIGN

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Abstract. *This paper presents the most significant aspects of the present and future of diesel engine. Diesel engine evolution is presented since its beginning at the latest years of the XIX century to present days. In the first part of the paper, key aspects influencing diesel engine evolution are presented: legislation, technological evolution and user requirements.*
The second part of the paper is devoted to the main areas of diesel engine's technological evolution, which has been revolutionary in recent years. Electronic injection, exhaust gas recirculation, supercharging, new combustion systems, variable valve timing systems, and exhaust gas after-treatment, are presented and main trends of their evolution discussed.

Keywords*: Diesel engine, technical evolution, forecasted evolution*

1. Introduction

In 1892 there was an important innovation in the development of internal combustion engines, when the German, Rudolf Diesel, proposed a new system based on the compression of air in order to reach a high enough temperature to provoke fuel self ignition, which was injected at the end of compression stroke. Diesel's original idea consisted of adapting the injection profile to piston movement in such a way that combustion temperature was kept constant, thus ensuring that the cycle was similar to that of Carnot.

Diesel's engine conception consisted of compressing a certain quantity of pure air inside the cylinder; the first part of this compression stroke (approximately half of the stroke) had to be carried out at a constant temperature by injecting fresh water into the cylinder (Cummins, 1993). The second part was carried out without water injection. With this method, the final compression pressure would be about 250 bar with a temperature of about 800ºC. At this point, the fuel would be slowly introduced, maintaining a constant temperature of 800ºC. Maximum cycle pressure was 90 bar and was obtained at the beginning of the expansion stroke. From this moment, the rest of the stroke was due to the expansion of the combustion gasses. The fuel used was finely pulverized coal.

Diesel's tests were sponsored by MAN and Fried Krupp and, after 5 years, they succeeded in developing a marketable petroleum engine. The compression pressure reached 32 bar and fuel injection was performed by compressed air at 45 bar. Initial constant temperature combustion concept was replaced by constant pressure combustion.

Although Diesel originally hoped to achieve 73% efficiency, his engine reached 23%, which was of much greater efficiency that any other machine of the time. This characteristic continues to distinguish his engine from others today.

Nowadays, diesel engine combustion is a hybrid of a constant volume process and a constant pressure process. In the case of large engines, the combustion is more similar to the latter, whilst in small engines the combustion is more similar to the former.

Rudolf Diesel's original concept of self-ignition is still valid today, as the combustion process is controlled by the start of injection. Nowadays, diesel oil is the chosen fuel for this kind of engine.

Nowadays, the diesel engine has a wide range of uses; car engines, heavy-duty vehicles, railway engines, industrial applications and large marine engines. In order to give an idea of this extensive range of uses, we need only point out that a car engine can displace 0.3 liters per cylinder, whilst a large marine engine can displace up to 1.7 m^3 per cylinder. This represents a ratio of more than 1:5000.

The aim of this paper is to discuss the future of diesel engines and to highlight the main aspects of its technological evolution. It is impossible to predict the long-term future of diesel engines due to the major changes affecting internal combustion engines, which will be explained in due course. We will therefore limit the scope of this paper to a range of 6 to 8 years.

2. Technological evolution

The importance of diesel engines has grown significantly in recent years and we can currently state, without exaggeration, that we are experiencing a drastic change in the design of internal combustion engines.

The reasons for this change are closely linked to the following aspects:

a) Legislation
b) Technical advances benefited by new experimental and theoretical techniques
c) User requirements

2.1. Legislation

Due to the huge impact of internal combustion engines on the environment, engine emission legislation has been made increasingly stricter. This has forced researchers to develop cleaner and quieter engines, thus resulting in notable improvements in emission control, both in pollutant formation and after-treatment systems.

Let us not forget that in recent years the admissible emission levels have been reduced to a tenth of their previous value, and a progressive reduction is forecast for the coming years. Figure 1 shows the admissible values of two the most characteristic diesel's pollutants, according to the different European laws. Engines currently on the market comply with the Euro IV standard and all factory engineers are already working to Euro V. It is possible that at this rate engines could become air filters in the largest urban areas.

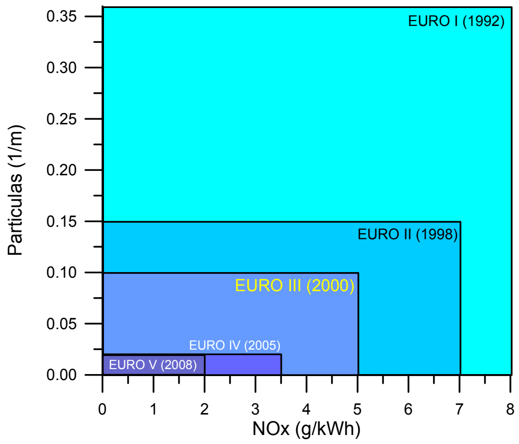

Figure 1. Evolution of the European emission regulations.

We believe that current efforts should focus on the reduction of fuel consumption, and consequently the reduction of CO2 emissions and the greenhouse effect. This is where the diesel engine could have advantages over other alternative power plants. Vehicles using engines that consume 4, or even 3 liters, per 100 kilometers are almost a reality.

The technological evolution of diesel engines in recent years has been spectacular. We have witnessed the practical disappearance of the divided combustion chamber engine (IDI), widely used in small cylinders, which is being substituted by the direct injection engines (DI), even in very small cylinders, unheard of some years ago. Figure 2 shows the evolution of ID and IDI engine sales, as well as the percentage of diesel engines in the car sales market. The substitution of IDI engines by DI engines is easily appreciated, as is the increase in diesel percentage.

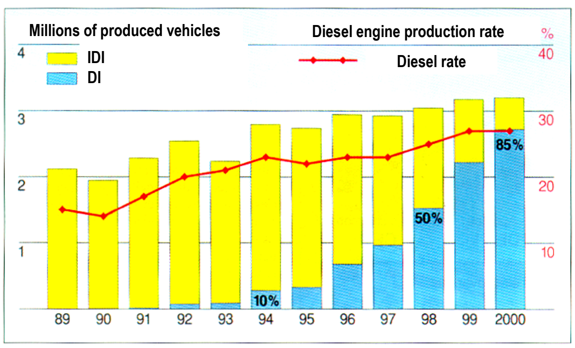

Figure 2. Evolution of the car fitted with diesel engines in EU.

2.1. Technical advances

The market introduction of new concepts in fuel injection systems, the increase in injection pressure, the possibility of mechanizing ever smaller elements with narrower discrepancies, and higher performance boosting systems are some of the advances that are supporting and improving this technology.

With regard to the current engine design it is worth pointing out one aspect, which albeit not fully developed, is possibly responsible for the current change we are facing: the introduction of electronics to engine management. On the electronics front, there are important advances that will come in an immediate term via the engine closed-loop control strategies.

Not long ago, there were very few parameters available for the optimization of the injection/combustion process within a diesel engine. Most in the contrary, us researchers have nowadays perhaps too many, and what is more dramatic: we do not know well enough how some of those parameters effect both the performance and engine emissions.

As soon as, in the very short term, the electronically controlled starting of both intake and exhaust valves is introduced, which we will talk about later on, it is possible that a second revolution comes, since we are currently experiencing the first one, with the use of electronic injection.

It is important to ask the cause for those ever-important technical advances. We believe it has been the development of new experimental and theoretical techniques, which has made it possible for these advances to exist.

Us immersed in this field find it difficult to conduct an objective evaluation, however it is worth remembering that instrumentation has developed enormously, and that it is possible today to measure and see phenomena taking place in the engines, that could not have been imagined in the recent past.

When it comes to numerical calculations, we believe we have already overcome the old debates confronting those stating that calculation programs would be more than enough for engine design and those who believed only in experimenting. Calculation programs are today an invaluable help for engine design and a complementary one for tests, which has allowed a very significant acceleration within engine development. Calculation programs continue to evolve as we manage to better comprehend the physical phenomena involved at each of the processes taking place within the engine, and it is foreseeable that it will become an even more important tool in the upcoming years in engine design.

2.1. User requirements

Another determining factor in the future evolution of automotive diesel engines is the ever more demanding requirements of the user in terms of performance, drivability and comfort.

Together with improvements in efficiency and reduction of emissions, we are experiencing a spectacular increase of the specific power of these engines, mainly thanks to electronic and automation improvements. Diesel engines with specific power higher than 60kw/liter are yet on the market and, from the user point of view, they are difficult to differentiate them from spark-ignited engines.

3. Highlits on the technological evolution

3.1. Electronic injection

The fuel injection system in diesel engines is in charge of feeding the precise fuel required at the right time, at each stage of the engine process. Furthermore, it needs to provide the fuel with the appropriate macro- and microscopic features required for its correct combustion within the chamber. Figure 3 represents an example of the injection spray within the combustion chamber.

Figure 3. Fuel spray appearance when using a 5-hole injector.

Since the most sophisticated systems and mechanical devices for regulation of diesel injection systems do not manage to comply with the future emissions' regulations, the introduction of modern electronic control devices has become necessary. These devices allow for the measurement of real physical magnitudes, as well as data storage, regulation, control and processing in offer to achieve the necessary requirements to meet the regulations. On the other hand, the introduction of direct injection diesel engines in the car market since 1988, has intensified the demand for highly flexible injection systems, since the system requirements are stressed even more in these type of engines, featuring a decrease in its dimensional characteristics (combustion chamber) and an increase in the engine rotational speed.

A flexible injection system is a great advantage for the proper operation of diesel engines. Main parameters to be controlled by the injection system are: start of injection, injected fuel mass, injection pressure, and injection profile.

Mechanical-based conventional systems are not able to manage all these parameters in an independent way, and electronic control devices are needed in order to increase the flexibility of the injection system. Injection regulation is now optimized depending on several input parameters (as user power requirements, engine speed, and engine characteristic temperatures and pressures). Once the optimum injection parameters are calculated by the electronic control unit (ECU), it acts over the injection system actuators in order to achieve the required injection settings.

Electronic diesel control (EDC) is nowadays an essential component of modern automotive engines. First prototypes appeared at the end of the 70s (Bosch, 1978), but it was very expensive and insecure. First common-rail (CR) system operating at 1200 bar appears in 1991. CR systems are simplified and improved during the 90s decade and are finally included in production vehicles in 1998-99.

Nowadays, there are several technical solutions to this conception, as common rail systems (CR), unit injector system (UI), and unit pump system (UP).

CR system is most common in diesel automotive engines, and offers a complete flexible and independent definition of all injection parameters listed above. A diagram of a CR system is shown in Fig. 4.

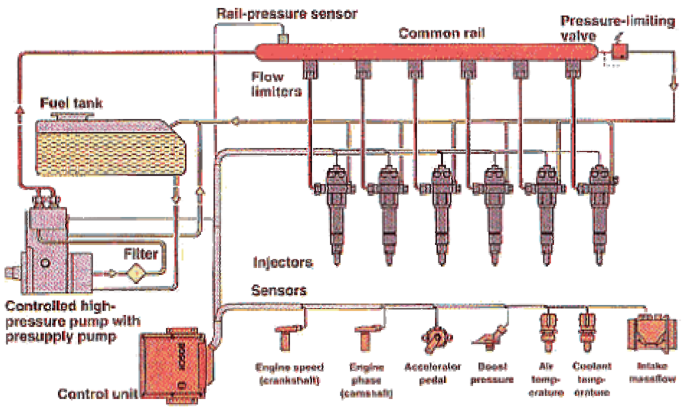

Figure 4. Diagram of a common-Rail (CR) injection system (from Robert Bosch, Gmbh.).

Electronic injection systems have meant a key factor in diesel engine improvement. Although they are of general application in the present days, they are not completely developed, as it is proved by the continuous evolution of these systems.

Main trends for next years aim to:

- increasing injection pressure (2200 bar),
- diminishing injector holes (diameters of 100 μm),
- adopting non-cylindrical injection holes,
- increasing versatility in the injection definition: increasing number of injections and achieving flexible fuel delivery profile. We highlight that last generation of CR systems is able to perform up to 5 different injections per stroke.

3.2. Exhaust gas recirculation (EGR)

One of the most important diesel engines' pollutants is nitrogen oxides, which are usually referred with the acronym NOx. NOx formation is related with combustion processes carried out at high temperature and with excess of oxygen. Both conditions are accomplished by the diesel engine combustion process.

There are several ways of reducing NOx production. The first one consists in decreasing the combustion temperature and pressure. This can be achieved by retarding the start of injection. However, this action also affects the engine efficiency in a negative way.

Another solution is using a multiple injection profile, causing the heat release law to avoid high temperatures at the combustion chamber. Hence NOx production is limited.

The EGR possibility consists in introducing a fraction of the exhaust burnt gases in the intake manifold. This system is known as exhaust gas recirculation (EGR). If the EGR fraction is increased, the content of inert gases of the intake mix is increased, thus diminishing the temperature of the combustion process and the NOx formation in consequence. Figure 5 and Fig. 6 clarify the effect of the EGR in some relevant parameters.

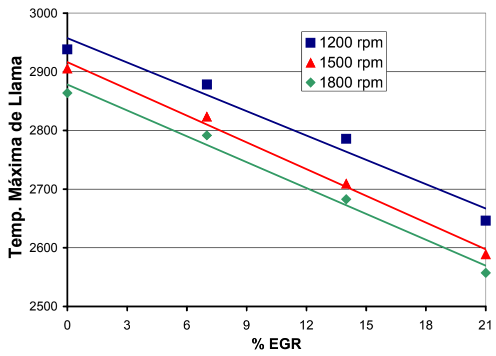

Figure 5. EGR effect on maximum combustion temperature.

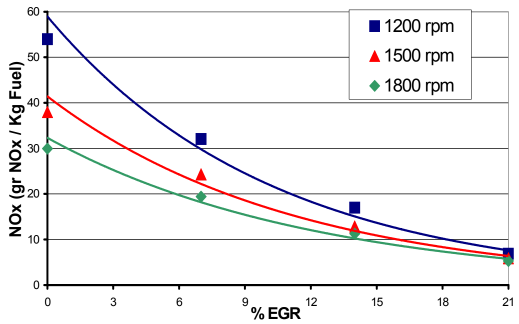

Figure 6. EGR effect on NOx emissions.

This technique was first used at the beginning of the 90s, and nowadays is very common technique. Main drawback of the EGR system is the increase of the particulate matter emission caused by the effective reduction in the oxygen concentration inside the cylinder. Usually EGR systems are used jointly with soot reduction systems.

Finally, in order to avoid the increase in the intake mix temperature when high EGR rates are used, it is a common technique cooling the exhaust gas to be recirculated. Note that increasing intake temperature affects in a negative way both NOx formation and engine volumetric efficiency.

It can be stated that EGR is a widely used technique. Last advances of the technology include EGR temperature control: cooled EGR is used in normal operation, while hot EGR is used in the low load region and at cold start. In our opinion, the sole application of the EGR will not be enough for complying with Euro V standard, although researchers are yet experiencing with 50% EGR rate.

3.3. Turbocharging

Supercharging the internal combustion engine is a practice coming from the very early days of the engine history (Zinner, 1978). German-born Daimler presents a patent in 1885 where the intake air compression benefits are explored; he proposed the application a pump similar to the one used for the scavenging process of the two-stroke engines. Also Diesel in 1896 considered the advantages of boosting his engine. Diesel used an reciprocating compressor powered by the engine itself, compressed air was stored in a deposit where the cooling of the compressed air was possible; this practice is near of today's intercoolers. Although Diesel succeed in improving engine performance (in comparison to the naturally aspirated engine), engine efficiency was ruined because of the incorrect matching between the engine and the compressor.

Sulzer's engineer Büchi was the pioneer in turbocharging with exhaust turbine. In 1905 he proposed a patent where an axial turbocharger matched with a turbine fed with the exhaust turbine was used for supercharging the engine. In this first patent all three machines (compressor, turbine and engine) were all mounted in the same axle. In a further patent, Büchi proposed a compact turbocharger, where the turbine and the turbocompressor were mounted on the axle but not the engine; this solution is still used. Figure 7 shows a scheme of a turbocharger.

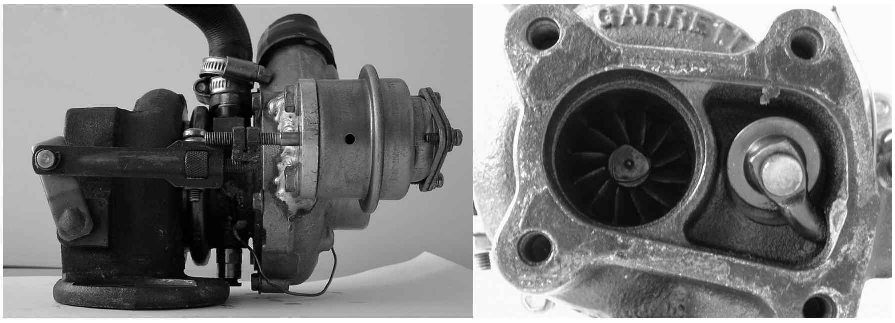

Figure 7. Two views of an automotive turbocharger with WG.

Turbocharger and engine matching is a complex issue. Diesel engines are reciprocating machines, thus with discontinuous air mass flow, operating range of these engines is quite wide in terms of intake pressure and air mass flow; on the other hand, turbomachines do their best in steady flow operation, and the operating range is narrower.

At low engine load, a turbine with a small effective section is needed in order to increase the exhaust manifold pressure, therefore sufficient power is provided to the compressor. On the other hand, at high engine speed, a turbine with small effective area will cause excessive turbocharger speed and exhaust manifold pressure, while a bigger turbine will suffice for providing the power required by the compressor. As a fixed geometry turbine can not be adapted to all operating situations, variable geometry solutions are used: waste-gate (WG) and variable geometry turbine (VGT).

WG has been, and it is still, a very used solution to the matching problem. It consists on diverting a part of the exhaust gases, thus decreasing available energy at the turbine inlet. Turbocharger showed in Fig. 7 is fitted with a WG.

The technically most sophisticated solution is VGT. VGT is able to adequate the turbine effective section to the operating requirements. VGT application allows the optimization of the matching for the different engine speeds, hence engine performance is improved. Depending on the engine operating conditions (engine load and speed, and also user requirements), turbine effective section is fixed. Figure 8 shows a VGT, which acts over the turbine blades angle.

Despite all the referred advantages, VGT application is not generalized because of manufacturing and cost difficulties. It is not easy to produce low-priced turbines with high efficiency and a reliable mechanic actuator system.

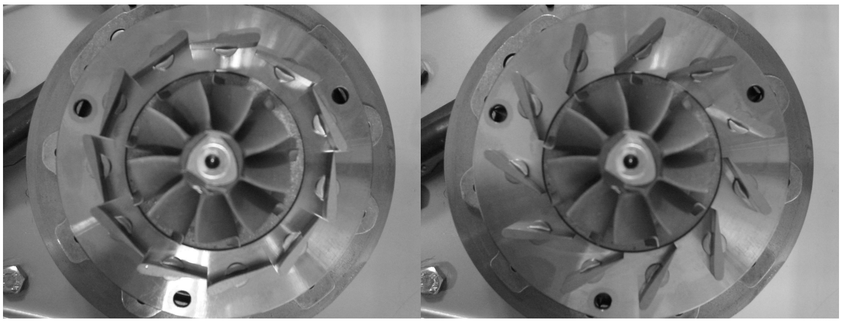

Figure 8. VGT in closed position (left) and open (right).

A last trend in turbocharging is using double-stage turbocharging, which is aimed to reach boost pressures beyond 4 bar. There are yet on the market bi-turbo diesel engines, and the trend will be increasing engine specific power with this technology (down sizing).

Finally, as a complement of the turbocharging methods, electrically driven compressors are being developed for improving transient torque response.

3.4. New combustion conceptions

As a direct consequence of the development of the injection system, and of the turbocharging and EGR systems, which allow a flexible control of both fueling and engine breathing, researchers have developed new combustion conceptions. These new combustion conceptions, named in different ways, are of very different characteristics (Pinchon, 2004).

In the case of diesel engines, main trend is the application of homogeneous charge combustion. Fuel and air homogeneous mixture is obtained by means of the very flexible electronic injection systems, while the combustion timing is controlled with the EGR rate in the mixture.

These new diesel combustion conceptions are not mature for the moment, but maybe they could be used for low load and speed conditions, while conventional combustion concept would be used at high load and speed conditions.

3.5. Variable valve timing (VVT)

Variable valve timing (VVT) development interest is mainly related to the will of improving engine performance, and comply with future pollutants emission regulations.

Today's most versatile VVT systems are those based on electro-hydraulic valves that act over the intake and exhaust valves by means of an hydraulic circuit of variable complexity. These systems are in development stage, and there exist several research prototypes in operation.

VVT systems currently on the market are mechanical systems that modify cam actuation mechanism. These systems can modify valve lift and timing in a restricted way. An example of one of these mechanical systems is shown in Fig. 9.

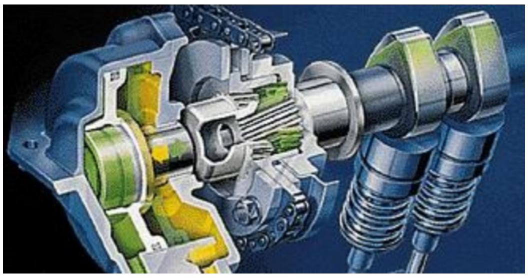

Figure 9. Electro-mechanic VVT system

Electro-hydraulic VVT systems will likely reach their maturity in few years and, from that moment, a second technologic revolution will be started. If current injection systems allow the flexible control of injection settings, future electro-hydraulic VVT would add the capacity of flexibly controlling engine breathing. Hence new strategies will be possible:

- Intake valve lift could control engine effective compression ratio. Thus cold start strategies could be improved, and compression work could be optimized for different engine loads and speeds.
- As valve timing could be varied in a flexible way, reverse flux at the intake and exhaust valves will be avoided, thus improving engine volumetric efficiency.
- Internal EGR could be performed when required, retaining a fraction of burnt gases at the exhaust stroke.
- Exhaust gas timing could control exhaust gas available energy, thus interacting with the turbocharging system.
- Fresh air shortcut could be induced in order to refrigerate exhaust valves and turbine at high engine loads.

3.6. Exhaust gas after-treatment

Main pollutant emissions in diesel engines are NOx and particulate matter, since CO and HC emissions are less critical. Optimizing engine operating conditions require the simultaneous reduction of these two main pollutants. However, when combustion process is modified in order to reduce NOx emissions, soot formation is increased. This is also true in the opposite sense.

Despite all new technologies (new electronic injection systems, EGR, VGT turbocharging), it seems only feasible to comply with emission regulations if the combustion process is optimized for the minimization of pollutant emissions. As only one of the pollutants may be minimized at the same time, after-treatment systems have become necessary. Figure 10 summarizes different possible strategies.

As shown in Fig. 10, there are two alternatives for reducing emissions through after-treatment devices:

Particulate matter (PM) trap. They are exhaust filters retaining all particulates exceeding the filter size. Main drawback is related with the dirtiness caused by the huge amount of particulate matter produced by diesel engines (about 1 kg per 50000 km in a car engine and 5 kg per 1000 km in a heavy-duty engine). This situation enforces the filter regeneration through the oxidation of the retained particulates. For regenerating the trap, some modern cars control the back-pressure increase associated with the filter dirtiness. When high particulate accumulation is detected, a retarded post-injection is used, thus increasing exhaust temperature. The temperature increase, with the addition of an additional catalyst, permits the particulate oxidation. Unfortunately, fuel consumption is increased during the regeneration, and also engine performances are affected. Figure 11 shows a PM trap.

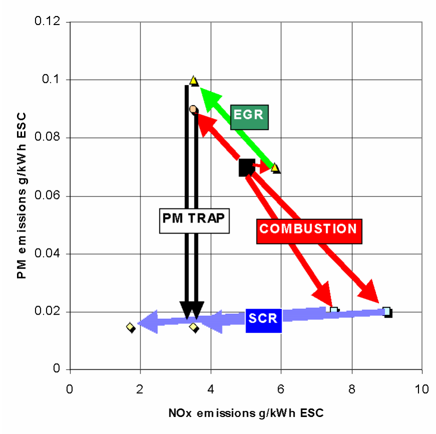

Figure 10. Strategies for emissions' control (Knecht, 2000).

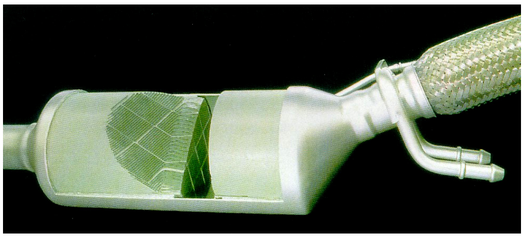

Figure 11. Section of a PM trap.

NOx catalysts. 3-way catalyst intensively used in the last decade in spark-ignited engines is not applicable to diesel engines. This kind of catalysts requires stoichiometric air to fuel ratio for simultaneously reducing NOx, HC and CO emissions. Diesel engines, which always burn in lean conditions, has oxygen excess thus inhibiting NOx reduction in the catalyst. As an alternative, two different NOx catalizers have been developed for diesel engines: adsorption catalysts, and selective catalysts.

Adsorption catalysts retain NOx and HC molecules in the catalyst's inner surface. This favors NOx reduction processes:

HC + NOX → N2 + CO2 + H2O (+ N2O)

Although adsorption catalysts have high efficiencies, they present two main drawbacks: sulfur-free fuel is needed in order to preserve the catalyst, and HC excess is required in the exhaust gas, which implies a consumption increase.

The second possibility is the use of selective reduction catalysts (SCR), which generate ammonia in order to reduce NOx with the oxygen. Ammonia is obtained form the reaction of water and urea, which is injected in the catalyst.

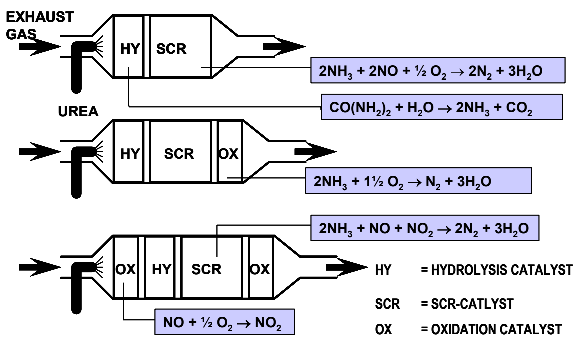

Figure 12. Different SCR configurations (Knecht, 2000).

Some SCR catalysts include oxidation catalysts for remove ammonia excess, or for transforming NO into NO2. All these SCR kinds are shown in Fig. 12. Urea addition is nowadays main drawback of SCR system, as there is not any distribution infrastructure.

As a conclusion, PM traps have been yet applied, but must be optimized in lifespan and the way the regeneration is performed. The future of NOx catalysts for diesel engines is not still clear. What is yet clear is that after-treatment will be a key for emission regulations fulfillment, as optimizing combustion process will not be sufficient.

3.7. Fuels

World Energy Council's and US Department of Energy's latest studies (GEIS, 2001; IEO, 2005) show that current fossil hydrocarbons reserve will widely last beyond 2070 with today's society necessities. Thus, petroleum fueled internal combustion engines will be used still for several decades.

On account of the requirements imposed by emission regulations, fuel quality became since 1992 a decisive factor for its fulfillment, since there is a direct relationship between high quality fuel use and the emission levels obtained with them in modern diesel engines.

Main drawbacks of present diesel fuel are:

- Sulfur content, which deteriorates present emission control devices. In addition, sulfur is present in some mechanisms of pollutant formation.
- Aromatic hydrocarbons content, which affects the combustion process, increasing flame temperature and thus NOx formation, soot formation and polyaromatic hydrocarbons emission.

Therefore fuel industry should not keep out of this legislation change process, but cooperate developing new products that support motor industry and its technological progress.

Fuel manufacturers' efforts face nowadays mainly the following investigation areas:

- Sulfur level reduction under 50 ppm. This reduction is a critical step for reducing engine's pollutant emissions and it would have a direct effect on emissions as it affects all vehicles.
- Aromatic content reduction under 10% in its composition, in order to reduce the number of particulate matter emitted and to improve fuel's knocking quality.
- H/C ratio increase, which would reduce emission levels due to its effect on flame's temperature.
- The development of detergent additives for diesel fuel, to achieve the injector's right cleaning which is fundamental in modern injection systems working with very high pressure.
- Cetane index increase up to 67.
- Further investigation about the benefits of water addition to fuel.
- The development of alternative fuels with high H/C ratio, as alcohols, biofuels and synthetic fuels like Fisher Troops. This is an area where research centers in the whole world are working but it still have to be solved its technological and economical production, and commercialization problems

4. Conclusions

Since 1892, when Rudolf Diesel created his first engine, the improving of these machines has been spectacular and we hope that this paper has achieved showing the great development of diesel engines.

It hasn't be discussed in this paper the subject of the evolution of materials in engine manufacturing but this would require a longer dissertation.

It must be stated that engines' evolution is based in several knowledge branches, whose breakthroughs make possible a development of diesel engines in recent years that can be called a revolution.

In a short-term (6 to 8 years) engines' subsistence is guaranteed and their evolution will be determined by future emission legislation.

We want to finish this paper highlighting that investigation is too focused in the topic of emissions and it would be necessary to direct more efforts to the improvement of fuel consumption (which means CO_2 reduction).

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6. Responsibility notice