Diesel Engine Modification Techniques to Minimize its Exhaust Emission (Theoretical Survey)

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Abstract: In recent time, the internal combustion engine powered vehicles have come under heavy attack due to the various problems created by them. The most serious of these is air pollution. The main pollutants contributed by the automobile are Carbon Monoxide (CO), Unburned Hydrocarbons (UBHC), Oxide of Nitrogen (NOX), Lead, Sulphur Oxide (SOX) and other particulate emissions. This paper gives a comprehensive overview of the current state of the art of diesel emission control technology. The main approach which have been used for this purpose is the various design modification processes of the diesel engine to minimize its exhaust gases emission and their impacts to the environment.

Keywords: Diesel engine, Exhaust gas, Particulate Matter, NOX, Gaseous Fuel, Energy Efficiency, Engine Modification, Low Temperature Combustion

I. INTRODUCTION

Diesel engine has provided the power units for transportation system and also important fuel economy and durability advantages for large heavy duty trucks, buses, non-road equipment and passengers cars. Indeed diesel engines powered both road and non-road equipments are the symbols of our modern technological society.

While they have many advantages, they also have the disadvantages of emitting significant amount of Particulate Matter (PM) and Oxide of Nitrogen (NOX) and to the lesser amount hydrocarbon (HC), Carbon monoxide (CO) and toxic air pollutant. Whereas the main problem facing the developing countries like, India and so on, however faces the same severe problems of pollution in their metropolitan cities, like Kano, Delhi, Bombay, Calcutta, Madras, Kanpur and so on, as in developed countries[1].

Particles emitted from diesel engines are small in most cases less than 2.5 microns in diameter. The particles are complex, consisting of a carbon core, adsorbed hydrocarbons from engine oil and diesel fuel, adsorbed sulfates, water, and inorganic materials such as those produced by engine wear. Because of their extremely small size and composition, the particles emitted by diesel engines have raised many health concerns. Health experts have expressed concern that diesel PM may contribute to or aggravate chronic lung diseases such as asthma, bronchitis, and emphysema[3].

However, because of the difficulties of conducting research on human subjects, and the large number of uncontrolled variables, assessing the effects of pollution on human health is difficult. Epidemiological studies, however, have show statistically significant correlations between pollutant level and health effects[4-6]. It is well known that pollutants can aggravate pre-existing respiratory ailments. The occurrence of both acute and chronic bronchitis, as well as emphysema, can be correlated with SOX and PM. the famous air pollution episodes in Donora, Pennsylvania (1948); London (1952); and New York (1966) results in many excess death and other effects. these episodes were all consequences of simultaneously high levels of SOX and particles. In recent re-evaluation of the lethal 1952 London fog, Bell and Davis [7] estimate that 12,000 excess deaths resulted from the episode. Carbon based particles may also contain adsorbed carcinogens. Only recently have researchers begun to understand the physical and biological interactions of PM and other pollutants with the human body [8]. For example, Oberdorster el al. [9] report that sufficiently small particles can pass between cell walls in the lung and enter the blood and lymph streams. These particles then can be deposited in bone marrow, lymph nodes, spleen, and heart where they can facilitate the production of oxidants. Such behaviour thus may provide a causal link between fine particles and cardiovascular diseases [8-9].

Despite health and environmental concerns, the diesel engine remains a popular means of powering trucks, buses, and other heavy equipment. Most buses and heavy-duty trucks are powered by diesel engines for good reasons. Diesel engines are reliable, fuel-efficient, easy to repair, and inexpensive to operate. One of the most impressive attributes of the diesel engine is its durability. In heavy-duty trucks, some engines have achieved operating lives of 1,000,000 miles or more. In Europe, more than 50 percent of the new cars sold each year are powered by a diesel engine. This is in part due to the superior fuel economy of the diesel, which delivers in excess of 30 percent higher miles per gallon than its gasoline counterpart. Engine manufacturers
have made significant advances in the performance characteristics of today’s diesel power plants. Unlike the diesel engines of just 10-15 years ago, which were considered noisy and sluggish, modern diesel engines deliver excellent low-end torque for superior acceleration. This combined with advanced transmissions eliminates the response lag of older diesel engines.

In response to public health concerns, a number of countries worldwide have established significantly lower exhaust emission limits for new diesel engines that are being phased in over the 2005-2015 timeframe. The U.S. EPA has mandated new regulations for on highway diesel trucks and passenger cars to reduce diesel emissions starting with the 2007 model year, with even further reductions in 2010. The emission control technologies discussed in this document represent state-of-the-art approaches that new vehicle manufacturers are using to meet existing and future emission regulations.

Figure 1 shows the current and future emission regulations around the world for heavy-duty diesel engines. The clear trend is toward reductions in PM and NOx usually in a two-stage approach. The first stage requires PM controls, such as diesel particulate filters. The second stage generally follows several years later with NOx controls. The tightest NOx levels remain as set by the U.S. EPA under their on-highway 2010 truck regulations [3].

Diesel engine calibration can be adjusted within the temperature-atmosphere combustion map into regions of higher PM or NOx emissions. A combustion environment that gives higher PM emissions will naturally result in lower NOx and vice-versa. Manufacturers can take advantage of this engine calibration control to specify a type of exhaust emission control that is best suited to meet regulations around the world. Therefore the technologies employed may vary depending on the demands of the emission standards in different countries [2].

II. VARIOUS DIESEL ENGINE DESIGN MODIFICATION TECHNIQUES

The emissions reductions achieved from 1990 through 1994 were massive: PM emissions of on-highway engines were reduced by 83% during that time. This was an extremely significant improvement as a consequence of this change, the old image of a diesel truck accelerating up a hill and projecting a cloud of dirty black soot into the air is a picture of the past. While there are still such engines on the road, no engine sold in the United States since 1994, properly maintained and burning the proper fuel, will smoke in this way.

The PM reduction was accomplished by improvements designed to ensure a more complete burn of fuel within the engine. The primary enhancements include improved fuel delivery systems, improved configuration of combustion chambers, and turbo charging.

The same wave of emissions reductions produced a 63% improvement in NOx emissions of on-highway engines. These reductions also were achieved primarily through modifications in the engine. The modifications helped control combustion temperature, including offsetting the temperature increases caused by systems adopted to reduce PM emissions. However HC, CO, SOX, NO and other substances emitted by diesel engine can also be reduced through the following engine modifications processes;

a) Variable Compression Ratio (VCR)
b) Modification of Combustion Chamber Configuration
c) Fuel Injection System Modification
d) High Pressure Fuel Injection
e) Engine Derating
f) Variable Injection Timing
Electronic Fuel Injection
Water Injection
Exhaust Gas Recirculation (EGR)
Exhaust Gas Recirculation (EGR)
Changing the Engine Circle

2.1 VARIABLE COMPRESSION RATIO (VCR);
Higher compression ratio (CR) is always desired to get better thermal efficiency but it increases NOX emissions. Research work were carried out to optimised CR and effective CR according to load on engine so as to get better overall efficiency as well as low engine out NOX.

Christensen et al. (1999) did experiment with variable compression ratio engine to demonstrate the multi-fuel capability of Homogenous Charge Compression Ratio (HCCR) engine. Secondary piston was placed in the cylinder head to achieved VCR from 10 to 28 by replacing one of the exhaust valves. They use different kind of mixtures ( mixture to iso-octane and n-heptanes as well as gasoline and diesel), for experimental purpose. All tests were carried out with an equivalence ratio of 0.33. Test result showed that pure n-heptanes (diesel) and iso-octane (gasoline) required CR of about 11 to 22 respectively to get auto ignition at TDC. Because of the poor atomization and vaporization of diesel fuel at low CR and at low inlet temperature (below 90°C), combustion quality become very poor. For all operating conditions, NOX emission observed were very low, while soot was generated only with diesel fuel. Study had shown that thermal efficiency was increased with increase CR but combustion efficiency was decrease leading to the minor variation in gross indicated efficiency. Higher amount of charge might be trapped in the crevice volume which reduces the efficiency with increase CR.

Laguito et al. (2007) analyzed the effect of CR on exhaust emissions came out from Premixed Charge Compression Ratio (PCCCR) diesel engine. Result indicated that the rate of combustion and proportion of diffusion combustion were reduced during injection at lower pressure and temperature with lower CR. Hence, soot and NOX emissions were reduced with the lower CR. However, maximum rate of pressure rise and hence the noise emissions were increased at higher engine load.

In general, CR was varied either by having a secondary piston or by adopting variable valve timing. Late intake valve closure reduced the effective CR and hence reduced the peak temperature leading to reduced NOX. However HC and CO were increase at low CR.[10]

2.2 IMPROVED OF COMBUSTION CHAMBER CONFIGURATION
More complete fuel combustion, and reduced PM emissions occur when fuel and air are mixed more evenly in the combustion chamber. Engine manufacturers have invested great effort in optimizing the features of combustion chambers to ensure the best possible mix. Modern combustion chamber design reflects extensive modelling of several design elements, including:

1) the shape and depth of the combustion chamber and the piston bowl (the small area at the top of the piston into which fuel is injected).
2) spiral-shaped intake ports that cause air to swirl as it enters the chamber;
3) the number of cylinder valves.
4) the placement of fuel injectors in the combustion chamber.[11]

2.3 FUEL INJECTION SYSTEM MODIFICATION;
Designing electronic controls and improving fuel injectors to deliver fuel at the best combination of injection pressure, injection timing and spray location allows the engine to efficiently burn the fuel without causing temperature spikes that increase NOx emissions.

Injection timing retard can reduce NOx emissions by lowering combustion pressures and temperatures. Injection timing retard, however, increases particulate emissions and may lower fuel economy. Increasing the injection rate can compensate for these drawbacks of delayed injection timing because the termination of fuel injection is not delayed. Injection timing retard for use in heavy-duty diesel engines will primarily involve integration in the control code, consisting of software modifications and not involving any hardware.

Injection rate shaping varies the rate of fuel injection to reduce NOx formation. Using the common-rail injection system, for example, a small, early burst of fuel (pilot injection) initially enters the combustion chamber, while injection of most of the fuel is delayed until the combustion chamber ignites. Due to the delayed injection, most of the fuel is combusted at lower peak temperatures, which reduces NOx formation. The electronic unit injector (EUI) also has the capacity for pilot injections to reduce NOx emissions.[12-14]

2.3.1 Test/Demonstration Projects
- NOx has been reduced up to 40% on on-road vehicles using an injection timing retard system approved under EPA’s urban bus rebuild/retrofit program.[15]
- In tests of a research Ricardo Proteus single-cylinder 2 litre engine, Tullis (1996) demonstrated a 16% NOx reduction using pilot injection.[16]
- Navistar and Siemens are developing electronically controlled, hydraulically actuated low- pressure injectors for use in heavy-duty diesel engines to meet EPA’s 2004 on-road diesel emission standards. The fuel injection system is scheduled to be ready for commercial use by the 2002 model year.[17]
2.4 HIGH PRESSURE FUEL INJECTION;

PM emissions are reduced through more complete combustion of fuel injected into the combustion chamber. More complete combustion can be achieved by improving the mix of air and fuel in the chamber. Modern high-pressure fuel injection systems force fuel into the combustion chamber through smaller diameter holes at higher pressure in excess of 25,000 pounds per square inch. This causes the fuel to break down into tiny droplets, thereby improving the air-fuel mix to achieve a more complete burn.[11]

2.5 ENGINE DERATING;

Substantial reductions in PM emission rates can result from lowering of the maximum fuelling rate of an engine. It is possible that many of the engines certified by MSHA are certified at or very near their maximum power where PM emissions are quite high. There is no restriction by MSHA on reducing the maximum power delivered by lowering the maximum fuel setting, i.e., derating. It is not unheard of that some mines choose to derate their engines to reduce DPM and CO emissions, reduce tire slippage and wear, and save on fuel costs. The MSHA list provides some insight into the effects of derating an engine on PM emissions. Table 4 shows the effects of derating on gaseous and DPM emissions from an Isuzu C240MA engine. The DPM emission rate can be reduced by 55% (calculated from the MSHA PI) with only a 7% reduction in power. If each engine is operated at the nameplate ventilation rate, the resulting DPM concentration is reduced by 62%.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Rating (hp @ rpm)</th>
<th>MSHA name plate ventilation rate (cfm)</th>
<th>MSHA PI (cfm)</th>
<th>MSHA approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isuzu C240MA</td>
<td>56.0 @ 3,000</td>
<td>2,500</td>
<td>5,500</td>
<td>7E-B085-0</td>
</tr>
<tr>
<td>Isuzu C240MA</td>
<td>52.0 @ 3,000</td>
<td>3,000</td>
<td>2,500</td>
<td>7E-B086-0</td>
</tr>
</tbody>
</table>

Table One; Derated Isuzu engine comparison

The comprehensive list of MSHA-approved engines provided on pages 5667-5668 of the coal rule [66 Fed. Reg. 5526 (2001)] have the Isuzu QD100-306 engine listed at 66 hp with a PI of 10,000 cfm and at 70 hp with a PI of 50,000 under the same approval number. Therefore, the reduction of 4 hp by limiting the fuelling rate results in an 80% reduction in the DPM emission rate for this engine. These two examples may be anomalies. PM emission rates for certified engines at powers lower than that of the certification testing may be obtained from the engine manufacturer. If the loss of power would not affect the performance of the equipment for a particular application, it is certainly advisable to check with the engine manufacturer on the emission reductions to be gained by derating the engine. If the derating is substantial, it is also advisable to check with the equipment or torque converter manufacturer to determine whether another converter should be used to obtain an optimum power match to the derated engine.

The proper procedures are explained by Forbush [2001][18]

2.6 VARIABLE INJECTION TIMING;

<table>
<thead>
<tr>
<th>Model Year</th>
<th>NOX Standard</th>
<th>% Change</th>
<th>PM Standard</th>
<th>% Change</th>
<th>PM Urban Bus Standard</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>10.7</td>
<td>-</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>-</td>
</tr>
<tr>
<td>1990</td>
<td>6.0</td>
<td>-44%</td>
<td>0.60</td>
<td>0%</td>
<td>0.60</td>
<td>0%</td>
</tr>
<tr>
<td>1991</td>
<td>5.0</td>
<td>-53%</td>
<td>0.25</td>
<td>-58%</td>
<td>0.25</td>
<td>-58%</td>
</tr>
<tr>
<td>1993</td>
<td>5.0</td>
<td>-53%</td>
<td>0.25</td>
<td>-58%</td>
<td>0.10</td>
<td>-83%</td>
</tr>
<tr>
<td>1994</td>
<td>5.0</td>
<td>-53%</td>
<td>0.10</td>
<td>-83%</td>
<td>0.05</td>
<td>-88%</td>
</tr>
<tr>
<td>1996</td>
<td>5.0</td>
<td>-53%</td>
<td>0.10</td>
<td>-83%</td>
<td>0.05</td>
<td>-92%</td>
</tr>
<tr>
<td>1998</td>
<td>4.0</td>
<td>-63%</td>
<td>0.10</td>
<td>-83%</td>
<td>0.05</td>
<td>-92%</td>
</tr>
<tr>
<td>2004</td>
<td>2.0a</td>
<td>-81%</td>
<td>0.10</td>
<td>-82%</td>
<td>0.05</td>
<td>-92%</td>
</tr>
<tr>
<td>2007</td>
<td>0.2</td>
<td>-98%</td>
<td>0.01</td>
<td>-97%</td>
<td>0.01</td>
<td>-98%</td>
</tr>
</tbody>
</table>

Table Two; Heavy-duty Diesel Engine Emission Standards (g/bhp-hr)
NOTE;  

a- compared to the base model year 1988. 
b- beginning in 1996, the certification level was 0.05 but the in-use level was 0.07.  
c- the 2004 NOX plus NMHC standard of 2.4g/bhp-hr is approximately equivalent to a NOX level 2.0.

They are used both to ensure a more complete fuel burn to reduce PM, and to control temperature to reduce NOx. In contrast, older diesel fuel injection systems used mechanical means to control the quantity and timing of fuel injection. With those systems, rapid ramp-up of engine speed such as acceleration with a heavy load led to excess fuel being injected. Much of this fuel was not burned and was emitted as soot, which created the black exhaust that many associate with old diesel engines.[11]

2.8 WATER INJECTION;

Water injection absorbs heat to vaporize the water, which lowers peak combustion temperatures and reduces NOx formation. Water injection is one of the few engine modifications that simultaneously reduces NOx and PM. Water injection does, though pose a number of technical challenges. A separate injection system with its own reservoir, injection lines, pump and injectors is required. Corrosion and deposits from dissolved impurities can present problems.[19]

2.8.1 Test/Demonstration Projects

California State University, Fresno (CSUF) achieved a maximum 65% NOx reduction using water injection during test stand work with a diesel truck engine. CSUF has developed a simple retrofit kit for water injection with minimal fuel economy impact.[20]

2.9 EXHAUST GAS RECIRCULATION (EGR);

Exhaust gas recirculation (mixing some exhaust gas with the intake air) is an established technology for cars that may be effective in heavy-duty diesel engines. While EGR systems designed for heavy-duty applications and face a different set of operating conditions and environmental considerations, existing field experience from light-duty diesel applications can ease the transition to the heavy-duty market segment.

In EGR, part of the exhaust gas is recirculated to the air intake manifold. The exhaust gases mix with air and then flow into the cylinders, where they dilute and cool the combusting gases. It is believed that intake air dilution, by decreasing the O2 concentration in the combustion process, causes most of the NOx reduction, [21]. Other factors once thought to be important, including heat absorption by the recirculated air, are now thought to be of less significance, [22]

Fuel economy penalties may range from 3-6% for EGR systems. Since EGR increases PM emissions, it needs to be coupled with a PM exhaust after-treatment such as a trap or a filter.

2.9.1 Test/Demonstration Projects

In a test program instituted by the Manufacturers of Emission Controls Association (MECA) and Southwest Research Institute, EGR achieved NOx+HC emissions of less than 2.5 g/bhp- hr. The test engine was a 1998 12.7 l Detroit Diesel Corporation (DDC), 400 hp, Series 60, selected to represent a typical current design on-road heavy-duty diesel engine, [3].

Southwest Research Institute conducted a demonstration using 2 heavy-duty diesel engines, a 5.9 litre B-series Cummin and an 11 litre Series 60 Detroit Diesel. The engines achieved 51% and 48% reductions in NOx emissions, respectively.[23].

Navistar/Rhone Poulenc recently announced that one of their prototype engines has achieved NOx emissions of 2.0 g/bhp-hr using a cerium-based fuel additive and particulate filter system in combination with EGR. With additional optimization, these exhaust emission control strategies can also be applied to non-road applications.[15].

Under the auspices of the California Energy Commission Clean Diesel Program, CeraMem will demonstrate an EGR system on a heavy-duty engine (DDC 6V-92). The system will be designed to reduce NOx to 2.0 g/bhp-hr, [24].

2.10 TURBOR CHARGING;

Turbo charging can both reduce PM emissions and improve fuel economy. A turbocharger compresses the air that enters the cylinder, forcing more air into the combustion chamber. The compressor is driven by a turbine, which in turn is powered by the engine's own exhaust. The increase in air in the combustion chamber offers two key advantages.

First, it enables fuel to burn more completely, reducing PM.

Second, it permits more fuel to be added to the chamber, generating more power than a similarly-sized engine without turbo charging.

By generating more power from a smaller displacement engine, turbo charging reduces engine weight and improves fuel economy, [11].

2.11 CHANGING THE ENGINE CIRCLE;

Changing a four-stroke diesel engine to operate on a two-stroke cycle can reduce combustion pressure and temperature and thereby reduce NOx. In a typical 4-stroke engine, air and fuel are drawn in as the piston moves down during the 1st stroke, (the intake stroke). The air is compressed as the piston travels back up during the 2nd stroke, (the compression stroke). The fuel auto ignites (in a diesel engine), driving the piston downward in the 3rd stroke, (the power stroke). The exhaust gases are pushed outward during the 4th stroke, (the exhaust stroke), [25].
In a 2-stroke engine, the exhaust of spent gases, followed by the intake of fresh air and fuel, occur as the piston travels downward during the power stroke. Auto ignition of the diesel fuel then occurs at the end of a compression stroke every time the piston approaches the top of the cylinder, instead of every other time, as is the case for a 4-stroke engine. Combustion is performed twice as often; the same power is produced with smaller explosions more often. The smaller explosion means reduced pressure and heat in the power production cycle, which reduces NOx emissions. To produce the smaller explosion, more air and less fuel is injected into the cylinders (the engine operates leaner). The leaner combustion ratio reduces PM and HC emissions, [26].

2.11.1 Test/Demonstration Projects

Rotec Design has developed the FreedomAir™ system which can be retrofitted onto any normal 4-stroke diesel engine into a TwinStroke™ engine. The FreedomAir™ system comprises one air piston per 2 engine cylinders. At the bottom of the engine’s power stroke, FreedomAir™ scavenges the combustion cylinder of exhaust gases. As the piston rises, FreedomAir™ pumps additional air into the cylinder. As the combustion cylinder comes to the top of the cycle, combustion is achieved in the normal manner. During the power stroke of the first cylinder, the FreedomAir™ is scavenging and priming the second combustion cylinder. This process is repeated with FreedomAir™ alternating between pairs of combustion cylinders.

A prototype attached to a Peugeot 2.1 litre, 4-cylinder indirect injection Turbocharged Peugeot 4-stroke diesel engine achieved NOx reductions of 65-75%. PM was also reduced 75-85%, and CO output decreased 24-44%. Power increased significantly across all RPM ranges (88% at 1250 RPM). Overall fuel consumption was reduced, [13]

III. CONCLUSION

Various engine design modifications are available that if applied to the present and future diesel engine design can minimize the harmful exhaust emissions e.g. Hydrocarbon, Carbon monoxide, Nitrogen Oxide e.t.c. to the extent that after treatment methods may not be of importance.

That engine design modification is the first step to be adopted by the designers and the manufacturers to minimize the emission effect claiming many lives and properties and distorting the environment as a whole. For instance, about 85% of the harmful emission from the diesel engine are due to the incomplete combustion. Thus, if fuel induction systems, combustion chamber configurations, and other important engine parameters are modified, other after treatment methods e.g. particulate filter, catalytic reduction, flow through oxidation catalyst may be just to add value to the engine.

REFERENCES

[13] Ibid.


