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EXHAUST EMISSIONS AND ITS CONTROL METHODS IN COMPRESSION IGNITION ENGINES: A REVIEW

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ABSTRACT−Extensive usage of automobiles has certain disadvantages and one of them is its negative effect on environment. Carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) come out as harmful products during incomplete combustion from internal combustion (IC) engines. As these substances affect human health, regulatory bodies impose increasingly stringent restrictions on the level of emissions coming out from IC engines. This trend suggests the urgent need for the investigation of all aspects relevant to emissions. It is required to modify existing engine technologies and to develop a better after-treatment system to achieve the upcoming emission norms. Diesel engines are generally preferred over gasoline engines due to their undisputed benefit of fuel economy and higher torque output. However, diesel engines produce higher emissions, particularly NO_x and PM. After-treatment systems are costly and occupy more space, hence, in-cylinder solutions are preferred in reducing emissions. Exhaust gas recirculation (EGR) technology has been utilized previously to reduce NO_x. Though it is quite successful for small engines, problem persists with large bore engines and with high rate of EGR. EGR helps in reducing NO_x, but increases particulate emissions and fuel consumption. Many in-cylinder solutions such as lower compression ratios, modified injection characteristics, improved air intake system etc. are required along with EGR to accomplish the future emission norms. Modern combustion techniques such as low temperature combustion (LTC), homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI) etc. would be helpful for reducing the exhaust emissions and improving the engine performance. However, controlling of autoignition timing and achieving wider operating range are the major challenges with these techniques. A comprehensive review of diesel engine performance and emission characteristics is given in this paper.

KEY WORDS: Diesel engine, Emissions, Oxides of nitrogen, Particulate matter, Exhaust gas recirculation, Low temperature combustion

1. INTRODUCTION

Now-a-days automobiles are extensively used because of their individual mobility, flexibility and travelling to any preferred location at any time. Currently more than 600 million automobiles exist worldwide. IC engines are widely used in automobiles because of their excellent power to weight ratio and smaller size. IC engines are also preferred in portable machinery and in locomotive engines.

Major emissions produced by IC engines are oxides of nitrogen (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM). Pollutants emitted by engines are a major concern because of their negative impact on the environment as well as on human health. Hence, stringent emission norms are continuously being imposed on IC engines.

During the mid-1960s, United States and later on, in early 1970s, Europe introduced safety and environment regulations, and imposed limits on CO, HC, NO_x, and particulate matter. Emission regulation in Europe is based on European Union research organization (EURO) norms and ultra low emission vehicles (ULEV), super ultra low emission vehicles (SULEV), zero emission vehicles (ZEV) standards are used in California. India has implemented Bharat norms in the early 2000s by taking EURO norms as a reference. As shown in Figure 1, exhaust emissions per test kilometer were reduced significantly from EURO-I to EURO-IV. Number mentioned in the bracket indicates the year in which the respective EURO standards have been implemented. EURO-V standard was applied from 2009 in European countries with further reduction of PM by 80% and NO_x by 20% compared to the EURO-IV standard. EURO-VI standard will be introduced in the year 2014 which requires additional reduction of NO_x by 55% compared to the EURO-V standard (Regulation/EC-715, 2007). Future norms for diesel engines mainly focus on reduction of NO_x emission.

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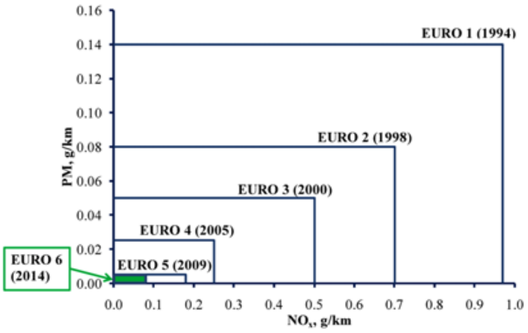

Figure 1. Progression of European emission standards for light commercial diesel vehicles.

2. EXHAUST EMISSIONS AND ITS CONSEQUENCES

It is difficult to achieve thermodynamic equilibrium during the combustion phenomena because of a) short time available for chemical oxidation processes, b) non-homogeneous mixture and c) non-uniform temperature distribution. Hence, incomplete combustion occurs inside the IC engines and products like CO and HC are present in the exhaust along with CO_2. Other than these sulphur compounds (SO_x) are formed from the sulphur content available in fuels and nitric oxides (NO_x) are formed by the reaction between nitrogen and oxygen at high temperatures.

Nitric oxide (NO) and nitrogen dioxide (NO_2) are collectively considered as NO_x, in which NO is predominant. Nitrogen oxides formation and consumption in combustion systems is discussed in detail by Hill and Smoot (Hill and Smoot, 2000). Normally NO is formed in three ways during combustion:

- Thermal NO formation (90% to 95%), which is mainly represented by Zeldovich mechanism,
- Rapid formation of prompt NO (5% to 10%) that take place in the flame front where local temperature reaches beyond 2500 K and
- Nitrogen contained in the fuel may be oxidized to produce NO (usually less than 1%).

Diesel engine produces much lower carbon dioxide, carbon monoxide and hydrocarbons, compared to gasoline engines. Particulate matter emissions mainly come out from diesel engines, while nitric oxide is normally produced in the both direct injection gasoline and diesel engines. NO_2 concentration is negligible in case of direct injection gasoline engines, while in diesel engines up to 30% of NO_x is found in the form of NO_2, which is more hazardous (Hilliard and Wheeler, 1979).

All engine emissions are having adverse effect on environment and human health. CO_2 contributes to changing the carbon cycle and modifying the climate by the "Green House Effect" and therefore it should be as low as possible. CO is highly toxic gas and its affinity for blood hemoglobin (Hb) is about 240 times greater than that of oxygen. CO blocks the Hb in the form of carboxy hemoglobin (CoHb) which reduces the availability of Hb for oxygen transport to the tissues (Degobert, 1995). CO causes dizziness and vomiting sensation. Even a small amount of CO affects mental function and visual ability.

NO plays role in fixation of hemoglobin and slight modification of the emphysema type. NO also reacts with moisture to form nitric acid which contributes to acid rain. NO_2 is insoluble and can penetrate deeply into the pulmonary system, thus killing specific cells in the lungs and damage the pulmonary functions. Hydrocarbons, particulate matters and SO_2 are considered just as irritants (Degobert, 1995).

3. EMISSION CONTROL METHODS

Modification of current IC engine design and development of effective after-treatment systems are required to fulfill the requirements of the future emission norms. Emissions from IC engines have already been controlled to a certain extent by precise fuel metering, quality of air supply, better fuel-air mixing, using homogeneous mixtures, lower combustion temperatures, precise ignition timing, and fully computerized engine management. These techniques are just sufficient to meet the current emission regulations. However, better technologies are needed to meet future severe emission norms. Along with these, quality of fuel plays an important role in reducing emissions and enhancing performance of IC engines.

3.1. Exhaust Gas After-treatment

Exhaust gas after-treatment system is usually used to chemically treat the exhaust gases produced from IC engines. Hazardous exhaust gases like CO, HC, and NO_x are chemically treated with oxidization and reduction processes, outside the engine before letting it to the atmosphere.

3.1.1. Three-way catalytic converter

The three-way catalytic converter is used to reduce NO_x along with the oxidization of CO and HC. Oxidation and reduction are simultaneously possible only when the engine runs using near stoichiometric mixture. The converter consists of a ceramic matrix or corrugated metal, bundled with a wash coat to provide a large surface area for chemical reactions. The wash coat is composed of actual catalyst materials, which consist of noble metals like platinum (Pt), rhodium (Rh) and palladium (Pd). Pt and Rh are used as reduction catalyst, while Pt and Pd are used as oxidization catalyst (Twigg, 2011).

Normally three-way catalytic converters achieved good conversion rates (~ 80%) and have a long service life in range of 400ºC to 800ºC temperature. They are ineffective at exhaust gas temperatures below 250ºC, and will be destroyed at exhaust gas temperatures above 1000ºC. Lead and lead compounds reduce the effectiveness of catalysts, so this technology works better with the introduction of unleaded gasoline (Vora, 2000).

Three-way catalytic converters are suitable for gasoline engines which normally run with near stoichiometric mixture. Diesel engines always run on an overall lean mixture, hence benefit of NO_x reduction by this catalyst is very less.

3.1.2. Oxidizing catalytic converter

Requirement of reduction of CO and HC emissions are the only reason for introducing oxidizing catalytic converters. Along with reduction of CO and HC emissions, hydrocarbons absorbed by soot particles are also converted. As soon as the light off temperature (temperature at which the catalytic converter begins to function) is reached, conversion rates as high as 80% can be achieved. Percentage reduction of CO and HC emissions depend on catalytic coating, converter location and temperature levels. The effectiveness of reducing PM as well as lean NO_x emission provided by these catalysts is limited and thus cannot be considered as key strategies for achieving future emission standards (Heywood, 1988).

3.1.3. Diesel particulate filter

Particulate filters, developed based on ceramic monoliths, ceramic fibers and metal substrate, are used to absorb particulates of very small size (~ 0.1 μm). Particulate deposits promptly block the particulate filter which affects engine output and increases fuel consumption due to increased backpressure. Recent study by Bharat et al. (Bharat *et al.*, 2011) shows a reduction in engine efficiency and an increased emission level with the increased backpressure. So filter regeneration is required to remove their blocking. The high temperatures (~ 600ºC) required to burn off soot can only be achieved under full load condition (Fino and Specchia, 2008). Further development is required with alternative catalytic coatings, additive supported regeneration, electric heating and diesel combustor to achieve lower soot ignition temperatures.

Continuously regenerating trap (CRT) system consists of a catalyst and a soot filter to ensure continuous burn off by reactions between NO_2 and carbon compounds to form CO_2. SO_2 in the exhaust gases slows down NO_2 formation which reduces reaction at CRT. So, CRT works efficiently only with low sulphur diesel fuel (below 10 ppm) (Braess and Seiffert, 2005).

3.1.4. De-nitrogenation

Development of catalytic converters that can selectively convert oxides of nitrogen using HC or CO, even in presence of excess oxygen is a challenging task.

The following practical methods are possible for NO_x reduction in the after-treatment (Fernando *et al.*, 2006):

3.1.4.1. Non selective catalytic converter (NSCR)

In presence of Pt/ Cu zeolites, NO is converted to N_2 by the reaction:

$$4NO + 2CH_2 + O_2 \rightarrow 2N_2 + 2H_2O + 2CO_2$$

The catalyst used is still unsatisfactory due to long-term durability issues. Only 25% conversion rates are achieved within a narrow temperature window (250ºC to 300ºC).

3.1.4.2. Selective catalytic converter (SCR)

This technology is generally used in stationary units, in which NO is converted to N_2 by reacting with ammonia (NH_3).

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

$$2NO + 2NO_2 + 4NH_3 \rightarrow 4N_2 + 6H_2O$$

Use of this technology in the transport vehicle is impractical as storage of hazardous NH_3 in gaseous form is unacceptable for safety reasons. NH_3 may be extracted from urea, $(NH_2)_2CO$, as one of the options but has serious disadvantages related to handling, storage and injection into vehicles. Shimizu and Satsuma (Shimizu and Satsuma, 2007) have specified AdBlue (32.5% aqueous urea solution) as the standard precursor of ammonia for vehicle applications. Hsieh and his team have proposed sophisticated urea injection control strategies by using various feedback approaches such as model predictive control (Hsieh *et al.*, 2009), two-level nonlinear control (Hsieh *et al.*, 2010), two-cell back stepping based control (Hsieh and Wang, 2011). These strategies are useful to inject precise dose of urea which improve the efficiency of SCR in reducing the tailpipe NO_x. Other than conversion efficiency, thermal durability is also an important factor, so improved wash coat based monolith catalysts have been used. But, they have a high catalyzing potential to oxidize SO_2 into SO_3, which can be extremely damaging due to its acidic properties. To overcome this problem, iron and copper exchanged zeolite coatings have been developed by Gieshoff *et al.* (2001) which also gave better performance compared to standard wash coat catalysts.

3.1.4.3. NO_x storage catalyst

In a well-known regeneration process (Boegner *et al.*, 1995), NO in exhaust gas is oxidized to NO_2 in presence of Pt catalyst during lean mixture operation of the engine. NO_2 reacts with barium carbonate ($BaCO_3$) and absorbed in the form of barium nitrate, $Ba(NO_3)_2$. Once, barium carbonate is fully converted into barium nitrate then the storage catalyst must be regenerated. When engine runs with rich mixture, barium nitrate rejects NO_2 which helps in oxidizing CO and HC. NO_2 itself gets converted into N_2 on the Pt catalyst, while barium nitrate reconverted into barium carbonate.

SO_2 conversion along with NO_x creates big problems during storage process. It competes with NO for adsorption space on the platinum thereby slowing down NO_2 formation. It consumes barium carbonate (the storage medium) that reduces the NO_x conversion rate in the long run. Therefore, NO_x storage catalyst works efficiently only with sulphur free fuels.

Exhaust gas after treatment offers solution for reduction of emissions, but is costly and occupy a large space. It has also been observed that sulphur free fuels are required to achieve better conversion efficiency with after-treatment systems. More attention in this review is focused on in-cylinder solutions.

3.2. In-cylinder Solutions

In-cylinder solutions are a better way to reduce emissions during combustion process itself. Figure 2 shows various in-cylinder technologies proposed earlier such as higher compression ratio, modified fuel injection systems, intake air management, electronic engine control, exhaust gas recirculation (EGR) etc. to achieve emission standards (Flynn *et al.*, 1999). However, the simultaneous reduction of NO_x and PM becomes a major issue in diesel engines to meet the requirements of future emission standards with these technologies.

Alriksson and Denbratt (Alriksson and Denbratt, 2006) plotted the equivalence ratio (Φ)-temperature (*T*) map for soot and NO concentrations using the SENKIN code with a surrogate diesel fuel, a mixture of n-heptane and toluene. Homogeneous mixtures of various Φ and *T* values are given as the inputs for the code. The results showed that the local combustion temperature should be kept below 2200 K to avoid high NO concentrations for low equivalence ratios. At high equivalence ratios, it becomes necessary to further decrease the maximum allowable temperature to avoid soot formation. Typical NO_x and soot production during combustion process in diesel engines is shown on Φ-*T* plane by Kitamura *et al*. (2002). It showed that low temperature combustion (LTC) with uniform mixture ratio of less than stoichiometric is required to achieve upcoming emission standards. Similar results were observed by Potter and Durrett (2006). The results, as shown in Figure 3, show that the NO and soot formation areas are completely avoided by keeping the combustion temperature very low (~1650 K) and equivalence ratio less than 2. The conventional diesel combustion and low temperature combustion processes were also demonstrated on Φ-*T* plane in Figure 3 (Potter and Durrett, 2006). Figure 3 indicates that NO_x and soot emissions can be reduced simultaneously with LTC.

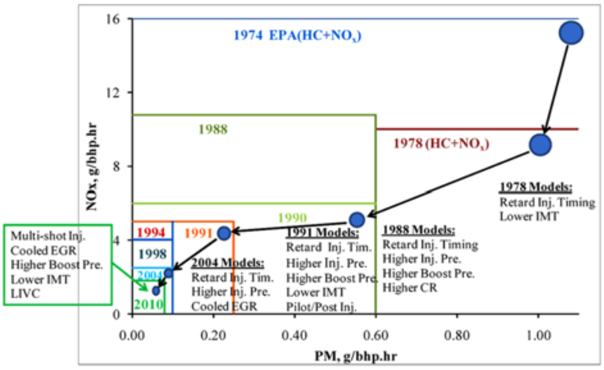

Figure 2. Advancement in in-cylinder technologies to achieve low NO_x and PM.

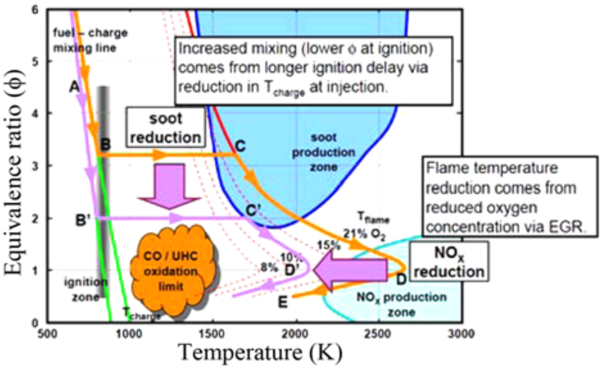

Figure 3. Conventional diesel combustion and low temperature combustion process on the Φ-*T* plane (Potter and Durrett, 2006).

Combustion temperature may be kept low by retarding the injection timing, by decreasing compression ratio and by increasing amount of charge dilution. However, soot emissions are increased because of low temperature. Soot formation may be reduced by having a homogeneous mixture of fuel and air with $\Phi \leq 1$.

3.2.1. Fuel injection characteristics

Fuel injection pressure, timing, duration etc. are important parameters to achieve better performance and low emissions. Study of pulse spray, heat release mode and emissions analysis were carried out by Su *et al*. (2004) at three different diesel combustion modes: forward concentrated, post concentrated and dispersed mode (DS, also known as MULINBUMP). Dispersed mode was achieved by early fuel injection with multi-pulse. It can be concluded from their analysis that thermo-efficiency of a DS mode working cycle was approximately as high as a conventional diesel cycle, while emissions of NO_x and soot were reduced simultaneously. The results indicate that the short injection pulse width provides a better fuel evaporation and mixing rate for early injection cases and the short injection dwell time shows more uniform stratification of the fuel for late injection cases. They also concluded that the DS combustion mode was a promising way in reaching the objective of higher efficiency and lower emissions for a wide range of engine loads.

In the work of Asad *et al*. (2008), various fuel injection strategies were studied to reduce emissions with improved efficiency of diesel engines. Experiments were carried out for the single and two injection strategies, with EGR sweep and maintained a constant combustion phasing i.e. CA50 (crank angle at which 50% of the total fuel mass is burnt). Combustion phasing was kept constant by changing start of injection (SOI). Based on experimental results, single shot with heavy EGR at low loads and multiple early injections for medium loads were suggested to get better fuel efficiency with Low Temperature Combustion (LTC). They also suggested that high load operation may be enabled with split-burning LTC, which is a combination of homogeneous charge compression ignition (HCCI) and post-TDC late combustion. The results showed that multi-pulse injection strategy is required to attain a lean fuel-air mixture of high homogeneity at higher engine load. Figure 4 shows the variations of NO_x and soot at different EGR levels with different injection strategies. Asad *et al*. (2008) have obtained very low values for NO_x and soot with 3-shot injection compared to single shot injection at an IMEP of 3.1 bar as shown in Figure 4. Experimental results, though not shown here, also indicated that HC was more sensitive to fuel injection strategies, while CO depends on EGR rate. Mobasheri *et al*. (2012) have also observed similar kind of result with high pressure (~ 1000 bar) split fuel injection techniques. Their result shows that optimized split injection (5%, 25%, 25%, 25% and 20% fuel injected at 30, 9, 0, -9 and -35 CAD bTDC respectively) was very effective for reducing NO_x and soot emissions compared to the single injection.

Shuai *et al*. (2009) investigated the effects of injection timing and rate-shape on LTC by using KIVA-CHEMKIN CFD code with an improved spray model to simulate the spray and combustion processes. Early and late injection timings and seven different injection rate-shapes were considered for simulation purpose. Their analysis indicated that early injection timing is better for lower soot, HC and CO emissions than late injection timing, but not for NO_x emissions. It was also observed that a short duration of injection and large percentage of fuel injected at the beginning of injection are suitable for lower soot emissions. However, injection rate-shapes were not significant for NO_x emissions. Increase in NO emissions with advancing injection timing was also observed by Verbiezen *et al*. (2007). They observed that only a small portion of the combustion chamber is responsible for the bulk of the NO that is produced. NO formation was reduced by using the split fuel injection strategy. Similar observations were reported by Jayashankara and Ganesan (2010) in their numerical study. Advanced injection timing results in increase of NO_x emissions but the soot emissions showed increasing trend up to a certain crank angle then started decreasing, in their investigations.

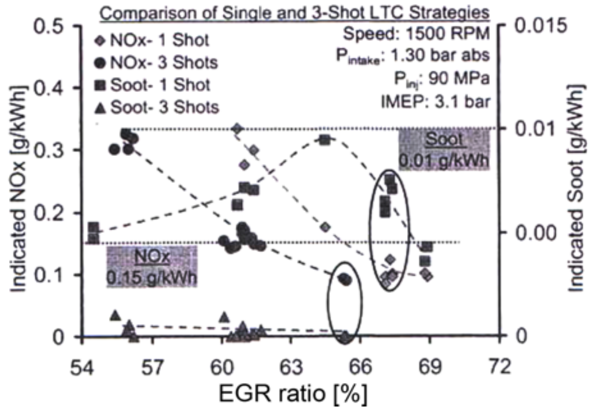

Figure 4. NO_x and soot emissions for single and three injection strategies (Asad *et al*., 2008).

Thurnheer *et al*. (2011) conducted experiments with varying pilot, main and post injection timings. Result showed that soot emissions were reduced with pilot injection, but NO_x emissions were increased. Post injection reduced the NO_x emissions, but soot emissions were increased drastically. However, fuel conversion efficiency was decreased with both injection strategies.

The air fuel mixing and combustion were investigated by Fang *et al*. (2009) with the help of optical diesel engine using retarded injection strategy. Their results showed a longer ignition delay, with a flatter and wider heat release rate curve, with retarded injection timing of -2 CAD bTDC. Because of that, simultaneous reduction of NO_x and soot emissions was achieved. It was observed that higher injection pressure of 1000 bar helps in further reduction of soot but it increased NO_x emissions.

Subramanian *et al*. (2009) carried out experiments on a single cylinder, four-stroke, DI diesel engine with partial HCCI Mode. They installed a low pressure auxiliary injection system at intake manifold to achieve premixed charge compression ignition (PCCI). The results showed that simultaneous reduction of NO_x and soot without affecting thermal efficiency can be achieved at an optimum fuel air premix value of around 20%. However, CO and HC emissions increased with increase in premix fractions.

Som *et al*. (2010) have analyzed the effect of nozzle orifice geometry on spray, combustion and emission characteristics under diesel engine conditions. The effect of three different orifice geometries viz. base nozzle, conical nozzle and hydroground nozzle were examined numerically and experimentally. It was observed that conicity and hydrogriding significantly reduced cavitation and turbulence levels inside the nozzle orifice. This resulted in slowing down of primary breakup which increased spray penetration and reduced dispersion. The flame lift-off lengths, mainly related to the rate of fuel injection and fuel air mixing, were the highest and lowest for the hydroground and conical nozzles, respectively. Studies have also shown that the influence of nozzle geometry was more pronounced on soot than on NO_x emissions. A hydrogroung nozzle was observed to be most efficient for NO_x and soot trade-off.

Orifice diameter also plays an important role in fuel spray penetration and atomization, hence in combustion phenomena. An effect of orifice diameter on diesel fuel jet soot was observed by Pickett and Siebers (2002). Their results showed that soot emissions were decreased with decreasing orifice diameter of nozzles. Non-sooting diesel fuel jets were realized using an orifice with 0.05 mm diameter, during their investigations. Desantes *et al.* (2011) studied the effect of nozzle geometry on combustion characteristics under cold start conditions. As opposed to the expectation, results indicated that for cold start conditions, ignition probability decreased if fuel injection velocity was increased or if the amount of injected mass per orifice was reduced, which was induced with smaller nozzle diameter or higher number of nozzles, respectively.

Icingur and Altiparmak (2003) studied the effect of varying injection pressure on a four cylinder DI diesel engine. Though, higher pressure demonstrated to give a better thermal efficiency and lower particulate matter (PM), it also resulted in higher exhaust NO concentration. Similar kind of results were observed by Fang *et al.* (2008, 2009). They did experiments on an optically accessible HSDI diesel engine to investigate influence of injection pressure in the range of 600 to 1000 bar, injection timing and EGR rate. Results indicated that higher injection pressure was favorable for soot reduction with little power penalty, but the NO_x was increased. Lower soot emissions have been observed with 1000 bar injection pressure compared to that with 600 bar. These results also support the experimental observation by Celikten (2003).

It can be concluded that early injection timing and higher injection pressures are better for lower soot, HC and CO emissions than late injection timing, but not for NO_x emissions. However, NO_x formation can be reduced by using split fuel injection process.

3.2.2. Air intake improvements

Henein *et al.* (2006) had investigated the effect of injection pressure and swirl motion on diesel engine-out emissions in conventional and advanced combustion regimes. Results in Figure 5 show that NO_x reduces while soot increases with increased EGR in conventional combustion regime. But reduction in soot emissions were observed with increased EGR in low temperature combustion (LTC) regime. Their results, as shown in Figure 5, indicate that soot emissions were reduced by applying higher injection pressures (1200 bar) and a moderate increase in the swirl ratio. Penalty in fuel economy and higher CO emissions were observed with the higher EGR rates. In addition to this, increase in energy requirement for higher injection pressure and increase in the cooling losses were also observed by investigators (Henein *et al.*, 2006).

Pickett and Siebers (2004) had found a trend of decreasing soot with decreasing equivalence ratio, and soot was no longer measurable within the fuel jet when equivalence ratio was decreased to a value of less than 2. A decrease in soot was also observed with decrease in ambient gas temperature, decrease in ambient gas density and increase in injection pressure. Lift off length, soot formation rates, soot oxidation rates and residence time play a very important role for the presence of soot in fuel jet.

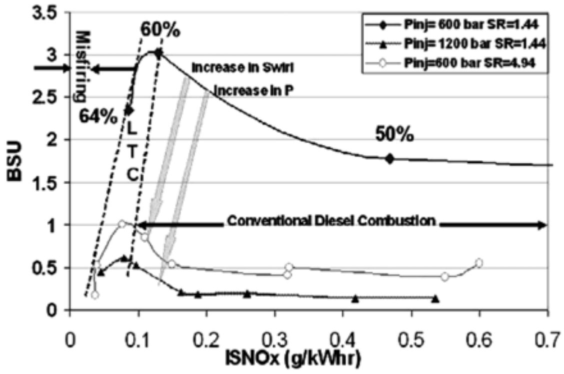

Figure 5. Effect of injection pressure, swirl and EGR on BSU and $ISNO_x$ (Henein *et al.*, 2006).

Ehleskog *et al.* (2009) had analyzed the effects of higher injection pressure (in range of 1750 to 2400 bar), EGR and charge air pressure on combustion and emissions of a single cylinder diesel engine. AVL visioscope was used for visualizing the combustion process and determining the flame temperature and soot level. The results showed that soot emissions were increased with higher EGR (30%) because of reduction in oxidation rates of soot. Higher soot oxidation, hence low soot emissions were observed with higher needle operating pressure. No effect on engine-out soot emissions were observed with higher charge air pressure (2 bar). Higher charge pressure, without EGR, reduced the combustion temperature and hence lower NO_x due to the availability of higher amount of air which absorbs more heat. However, higher charge pressure along with EGR resulted in higher NO_x.

On the contrary, higher NO_x and lower soot emissions were observed by Jayashankara and Ganesan (2010) in their numerical study, with higher charge pressure and without EGR. Higher rate of soot oxidation is the reason for reduction of soot emissions with higher intake pressure (1.71 bar) while increase in NO_x is because of excess air according to authors' explanation. These contradictory results might have been observed because of combined effect of injection strategies and intake charge pressure on combustion phenomena.

3.2.3. Variable compression ratio (VCR)

Higher compression ratio (CR) is always desired to get better thermal efficiency but it increases NO_x emissions. Research works were carried out to optimize CR and effective CR according to load on engine so as to get better overall efficiency as well as low engine-out NO_x.

Christensen *et al*. (1999) did experiments with variable compression ratio engine to demonstrate the multi fuel capability of HCCI engine. Secondary piston was placed in the cylinder head to achieve VCR from 10 to 28 by replacing one of the exhaust valves. They used different kind of fuel mixtures (mixture of iso-octane and n-heptane as well as gasoline and diesel) for experimental purpose. All tests were carried out with an equivalence ratio of 0.33. Test results showed that pure n-heptane (diesel) and iso-octane (gasoline) required a CR of about 11 and 22 respectively to get autoignition at TDC. Because of the poor atomization and vaporization of diesel fuel at low CR and at low inlet temperature (below 90ºC), combustion quality became very poor. For all operating conditions, NO_x emissions observed were very low, while soot was generated only with diesel fuel. Studies had shown that thermal efficiency was increased with increased CR but combustion efficiency was decreased leading to a minor variation in gross indicated efficiency. Higher amount of charge might be trapped in crevice volume which reduces the combustion efficiency with increased CR.

Murata *et al*. (2008) had proposed Miller-PCCI combustion in diesel engine with a variable valve timing (VVT) mechanism. Figure 6 indicates that NO_x and soot emissions were reduced drastically with large amount of EGR and early fuel injection (40 CAD bTDC) with late intake valve closing (LIVC). Because of impingement and insufficient vaporized diesel droplets on the piston cavity wall, low combustion efficiency was observed. To overcome this disadvantage, fuel injection near TDC (-4.4 CAD bTDC) was adopted with Miller-PCCI combustion. Higher gas density and temperature near TDC would be helpful to achieve better vaporization and to avoid wall impingement. Experimental results showed that Miller-PCCI (premixed charge compression ignition) combustion was achieved for a wide range of engine speeds and loads.

Late intake valve closing (LIVC) was also proposed by He *et al*. (2008) for emissions control strategy. Fully flexible valve actuation system was used to achieve LIVC. Effective compression ratio can be reduced by delaying intake valve closing (IVC). Results show that 25-50% NO_x can be reduced with LIVC at constant values of combustion phasing, inlet manifold temperature, air fuel ratio and EGR. LIVC increases the ignition delay, hence reduces the soot emissions at all operating conditions. HC and CO are increased due to LIVC, but CO may be reduced with LIVC-PCCI combination. Major disadvantage of LIVC is that it reduces the volumetric efficiency. At high load, NO_x reduction with LIVC would cause either high smoke or high HC and CO emissions. LIVC increases the combustion noise, but in combination with PCCI the noise may be reduced.

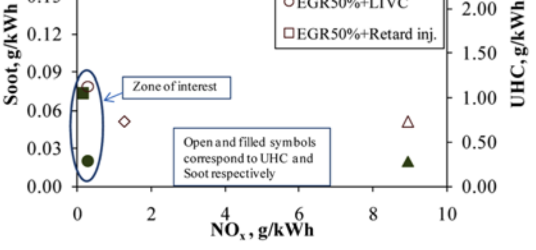

Figure 6. Simultaneous reduction of NO_x and soot by adopting Miller-PCCI combustion.

Laguitton *et al*. (2007) analyzed the effect of compression ratio on exhaust emissions came out from a PCCI diesel engine. Results indicated that the rate of combustion and proportion of diffusion combustion were reduced during the injection at lower pressure and temperature with the lower compression ratio. Hence, soot and NO_x emissions were reduced with the lower CR. However, maximum rate of pressure rise and hence the noise emissions were increased at higher engine loads.

In general, compression ratio 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 NO_x. However, HC and CO were increased at lower CR.

3.2.4. Exhaust gas recirculation

Exhaust gas recirculation is a proven, effective technique to reduce NO_x emissions from both CI and SI engines. EGR is a method in which a portion of engine exhaust gas is re-circulated to the combustion chambers through inlet system. This method involves displacing some of the oxygen introduced into the engine with inert gases, which absorbs heat during the combustion process, thus lowering the combustion temperature and hence reducing NO_x. Various EGR systems like low pressure loop (LPL), high pressure loop (HPL), laboratory simulated and treatment of EGR (cooling, oxidation, reforming) were discussed in detail by Zheng *et al*. (2004) in their review paper. Major concern is how aggressively EGR should be used at all speeds and all loads without affecting durability and performance of engines.

Kook and Bae (2005) had investigated the influence of charge dilution and injection timing on LTC and emissions in a single cylinder optical diesel engine. Performance and emissions were studied over a wide range of EGR rates (0–65%) and injection timings. The test results showed that the equivalence ratio was not reduced with increased EGR. Proper mixing can be achieved because of longer ignition delay with increased EGR. Hence, a mixing controlled combustion phase plays an important role under highly diluted operating conditions. High dilution rate with proper mixing is very essential to reduce NO_x, soot and CO emissions without affecting fuel consumption. It was found that early injection timing can be afforded only with a dilute inlet charge. However, maximum fuel conversion efficiency was observed at moderate charge dilution levels (~ 40% EGR) and slightly retarded injection timing (~ 5 CAD bTDC).

Maiboom *et al.* (2008) carried out an experimental work and studied various effects of EGR on combustion and emission of an automotive direct injection diesel engine. They have run the engine with cooled EGR circuit, variable geometry turbocharger and intercooler. Various rates of EGR were supplied to the engine at a constant air fuel ratio by varying boost pressure. Their results showed that NO_x always decreased with an increased EGR rate. Dilution was the most dominant effect with EGR at constant boost pressure, which gave adverse effect on soot formation and fuel consumption. But thermal effect becomes most dominant when EGR was supplied at constant A:F ratio by increasing the boost pressure. Maintaining constant A:F ratio is better to reduce NO_x and soot without compromising fuel consumption. However, constant A:F ratio may be achieved only for low EGR rates because of limitation of turbocharger.

The effects of reformed EGR on diesel NO_x emissions were investigated by Fernandez *et al.* (2009). Reformed EGR contains H_2 and CO rich gases, which were produced by the reaction between hydrocarbon fuels and exhaust gas over a catalyst in a fuel reformer. Fuel injected in a fuel reformer was compensated by reducing the amount of liquid fuel injected in the cylinder for the same power and torque. Reformed EGR is a promising alternative to reduce NO_x without compensating for smoke or brake specific fuel consumption (BSFC).

Millo *et al.* (2008) had done an experimental work with an advanced EGR control system for an automotive diesel engine. Engine with a new EGR control technique, based on the estimation of the O_2 concentration in the intake manifold was used for experiment purpose. NO_x emissions were extremely sensitive to the percentage of O_2 in the intake manifold. On the contrary, in the conventional EGR system, EGR flow control is based on the estimation of mass airflow (MAF) in the intake manifold. During transients, the gas dynamics of intake and exhaust systems and inertia of turbocharger play a role in case of MAF controlled technique, which supply low EGR flow rate compared to actual requirement, which increases NO_x emissions. Their results show that controlling EGR based on O_2 concentration is most suitable for reduction of NO_x emission during transient conditions.

The effect of EGR on combustion and emissions during cold start of a direct injection diesel engine had been studied by Peng *et al.* (2008). Choking valve was used in the exhaust line along with EGR valve for achieving better performance during cold start. CO, HC and PM produced during cold start are several times higher than that during warm start. Experimental results showed that proper amount of EGR introduced by partial opening of chocking valve and full opening of EGR valve during cold start promote the combustion process and hence reduce the average opacity.

Bose and Maji (2009) investigated engine performance and emissions of a single cylinder diesel engine using hydrogen as an inducted fuel and diesel as an injected fuel with exhaust gas recirculation. Flow of hydrogen was kept constant (0.15 kg/hr) during experiments, while amount of injected diesel fuel was varied according to the requirements of engine load. Engine produced more NO_x because of H_2 fuel (having higher heat release) used along with diesel fuel. This increased NO_x was compensated by modifying engine with EGR system. Experimental results showed that smoke is also reduced along with NO_x because of absence of carbon atoms in H_2. The similar kinds of observations were made by Saravanan and Nagarajan (2008). They had also used hydrogen as an inducted fuel and diesel as an injected fuel to run a single cylinder diesel engine on dual fuel mode. The results indicated that performance of the engine was improved with dual fuel operation compared to normal diesel mode, while NO_x and CO emissions were increased. Low smoke emissions were observed with the dual fuel mode. We think that EGR may be helpful in this case to reduce NO_x and smoke simultaneously.

Like EGR, reduction in local temperatures and hence NO emissions are also achieved with the help of water injection strategy. Several investigations were carried out with injection of water either into inlet manifold (Tauzia *et al.*, 2010; Hountalas *et al.*, 2007) or directly in the combustion chamber (Bedford *et al.*, 2000) or in emulsion with the fuel (Lif *et al.*, 2007; Song *et al.*, 2000). Their results show that substantial reduction in NO_x emissions can be achieved without a significant increase in PM emissions with water injection techniques. However, such techniques are not prominent like EGR because of system complexity and considerable increase in specific fuel consumption (SFC), HC and CO emissions.

EGR produces various effects like thermal, dilution and chemical effect during the combustion phenomena, which control combustion temperature and hence reduce NO_x production. But, adverse effect on soot was reported with EGR. Literature shows that simultaneous reduction in NO_x and soot may be achieved by properly mixed EGR with higher boost. It has been also observed that early injection timing and split injection strategy can be afforded only with the diluted inlet charge.

3.2.5. Modern combustion techniques

Dec (1997) had developed a conceptual model of DI diesel combustion based on laser-sheet imaging. Optical access research engine, with three windows: piston crown window, window located around the top of cylinder wall and window in cylinder head, was used for laser imaging diagnostics. Dec (2009) has also demonstrated the concept of advanced CI engines which had high efficiencies and very low emissions. Homogeneous charge compression ignition (HCCI) and low temperature combustion (LTC) techniques with various in-cylinder solutions such as higher CR, highly diluted charge, premixed or partially mixed charge etc. were considered. He had reported that LTC is commonly preferred over HCCI for diesel fuel, which employs high level of EGR and modified injection timings. LTC provides direct control over the combustion phasing through the control of injection timing, which helps in avoiding premature combustion that can occur with diesel fuelled HCCI.

Caton (2010) had analyzed the advantage of LTC combustion from thermodynamic point of view. Results showed that high CR, high EGR, lean mixture, short burn duration and high cylinder wall temperature were better to achieve higher thermal efficiency. NO_x emissions were almost insignificant when engine was operated in LTC modes. A computer simulation of the HCCI engine has been developed by Fiveland and Assanis (2000) for combustion and performance studies. Results showed that lowest CR and highest boost, in their range of parametric study, produced higher efficiency and higher power output.

A detailed chemical kinetics analysis of low temperature, non-sooting diesel combustion had been made by Aceves and Flowers (2005). They developed a model, which used a simplified mixing correlation and detailed chemical kinetics to analyze a parcel of fuel as it moves along the fuel jet from injection through evaporation and ignition. They concluded that soot precursors increase rapidly with increasing EGR, reaching a maximum and then decreasing rapidly as mixtures approaches to stoichiometric conditions. Results indicated that low combustion temperature and low equivalence ratio (less than 2) were preferred in achieving non-sooting combustion. Hence, gas temperature in combustion chamber and characteristic mixing time are important parameters to control soot production.

Ekoto *et al*. (2009) had analyzed sources of HC and CO emissions from a dilution-controlled LTC. Multi-dimensional, homogeneous reactor simulations had been performed for understanding of HC and CO distributions. HC and CO emissions were examined at fixed injection timing with a sweep in engine dilution (through EGR) and load. More diluted mixtures led to a lower combustion temperature, which reduces the oxidation of HC and CO. Hence, HC and CO emissions were increased. Results showed that squish volume was the dominant source of CO and a significant source of HC. HC and CO emissions were observed in simulations at the bowl and the central clearance volume region, but were not observed experimentally.

Sjoberg and Dec (2006) had explored the partial fuel stratification with two-stage ignition fuels to achieve smooth HCCI heat release rates with primary reference fuel 80 (PRF80; having octane number equal to 80). It was observed that partial fuel stratification offers good potential to achieve a staged combustion event (like diesel combustion) for fuels like gasoline which can be used to increase the high load limits of HCCI operation with acceptable noise and NO_x emissions. However, too much of partial stratification can quickly increase the NO_x emissions. The two-stage ignition fuels allowed more combustion retard and less cycle-to-cycle variations compared to single-stage ignition process. Partial fuel stratification was explored for PRF80 and PRF83 fuels using a two-pulse fuel injection strategy.

Literature shows that various parameters such as fuel injection characteristics, inlet air conditions, CR and EGR have strong influence on engine performance and emissions. They determine the environment for the combustion process and govern the rate and efficiency of vaporization, ignition and burning of the fuel. Hence, better performance and lower emissions can be achieved with proper combination of these parameters.

4. CONCLUSION

In this paper, a detailed review of diesel engine performance and emission characteristics has been given. Compared to gasoline engines, carbon dioxide, carbon monoxide and hydrocarbons produced in diesel engines are much lower. The issue of simultaneous control of NO_x and PM becomes more complex in diesel engines. Both after-treatment and in-cylinder technologies to reduce emissions in CI engines have been reviewed. It is understood that various technologies to reduce emissions can just meet the present emission regulations. Better in-cylinder and/or after-treatment technologies have to be developed to meet future stringent emission norms.

EGR seems to be a simple and most effective way of reducing NO_x emissions, but suitable measures need to be taken to reduce soot. There is a need to modify the EGR system along with some in-cylinder solutions viz. various injection techniques, charge conditions, late intake valve closing to improve the combustion phenomena and to reduce the emissions. Simultaneous reduction in NO_x and PM can be achieved with the modern combustion techniques such as LTC, HCCI, PCCI etc. LTC can be achieved with high level of EGR and modified injection timings. LTC provides direct control over the combustion phasing through the injection timing, which helps in avoiding premature combustion that can normally occur with diesel fuelled HCCI. Because of this, LTC is more favored than HCCI when engine uses diesel like fuels. However, achieving wider operating range and controlling HC and CO emissions are the major challenges with this technique. An optimized combination of all in-cylinder solutions is required to overcome these issues.

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