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Effects of EGR and other technologies to reduce emissions in IC engines –A Review

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Abstract*: The paper presents review of techniques that helps to go towards clean exhaust and highly efficient IC engines. Internal combustion engines are the primary power source of the transportation machinery, heavy duty vehicles used for caring goods, different types of earth movers, stationary engines to run different type of industry machines. IC engines produces many types of exhaust gases, the constituents of exhaust are very harmful and leads to major increase in the pollution levels of air. To control pollution levels worldwide legislations are made and limits are set for emissions produced by an engine. Presently in this review paper we discus about several techniques that are helpful to reduce the emissions in IC engines. We study in brief about the effects of various pretreatment techniques like LIVC, PCCI, EGR, Ignition delay, Water injection and other post treatment techniques like Catalytic convertors, NOx traps, SCR on engine performance and how they are able to fulfill new emission norms.*

Keywords*: IC Engines, EGR, PCCI, LIVC, SCR, NOx traps.*

1. Introduction

Internal combustion engine is a device that converts chemical energy of fuel into mechanical energy at output. Reports of many researchers have shown that after the year of 1990, due to peak growth of industries and automobiles [1] there is a major increase in the pollution levels of air. With increase in oil prices and due to more stringent emission requirements as [2] there is necessity to develop highly efficient and clean exhaust engines. Different technologies are used to develop engines having very high speed, bear high loads, good efficiency and low fuel consumption. But usually an efficient engine design is not always eco-friendly design. Basically engine exhaust have main constituents are CO, CO2, NOx and PM. All these contents pollute the atmosphere but some have more harmful effects than others. In this review paper we basically concentrate on techniques that are helpful to reduce NOx emissions. NOx is one of the constituent of exhaust that shows very harmful effects on our environment and human health. Reports shows that NOx leads to the formation of PAN, Aldehydes and other smog components that deteriorate environment and produce diseases like development of cyanosis especially at lips, fingers and toes, adverse changes in cell structure of lung wall and other diseases related to breath [3]. So to control NOx emissions, allowable limit of NOx was approximately set to 5g/kwh (3.7g/bhp-hr) according to international norms of year 2000, this limit can be easily achieved via conventional engine by some minute changes in the existing parameters such as increase the fuel injection pressure, the air boost ratio and some improvement of cooling system [4]. Europe and US governments takes very strict steps to control emissions and introduce new legislations where the value of contents of emission CO, CO2, NOx, PM are set up to very low or we can say approximately zero emissions [5] in future. In India also the Bharat stage series launches BS-V in 2021 and new challenging limits are set for emissions [6]. Now these values set up in the new norms are not possible to achieve by earlier methods. So it needs to devise alternative technical solutions to reduce emission. Numerous technologies are developed to decrease pollutant emissions that can be classified into two categories: pre treatment and post treatment techniques. Exhaust gas recirculation is one of the best pre treatment technique which enables the engine out raw emission to reach legislation levels [7]. In US, Diesel engines face tough challenges to meet stringent tier 2 bin 5 emission regulations [8, 9]. According to the legislation of year 2010 the values of major constitutes like NOx are limit to 0.07 g/mi, value of PM limit to 0.01g/mi, and 0.018g/mi limit on HCHO [10]. According to new legislation of Europeans emission standard Euro VI (2013) the value of main content NOx is 0.4 g/kwh [8, 11]. These emissions requirement challenges force the industrials and researcher to make better and better and focus on the major objective to decreasing NOx, PM, HC emissions without any compromise in engine efficiency and fuel economy.

Techniques developed time to time to fulfill new emission norms. Table below shows value of NOx set up under different legislations for different type of vehicles and methods used to achieve those emission norms [10, 12, 13].

Standard	Year	NOx limit	Technologies used
Type of vehicles : Light duty engines			
Euro 1/2	1992-96	NOx = 0.97-0.7 g/km	Introduced in DI and larger IDI Euro 1 engines, Non –cooled EGR became the main NOx reduction strategy in nearly all Euro 2 vehicles

Standard	Year	NOx limit	Technologies used
Euro 3/4	2000-05	NOx= 0.5-0.25 g/km	Cooled EGR used in larger size Euro 3 engines, and became the standard in Euro 4 and later diesel passenger cars and light trucks.
Type of vehicles : Heavy-Duty engines			
US 2004	2002-04	NOx ≈ 2 g/bhp-hr	Cooled EGR introduced on heavy-duty truck and bus engines by most manufacturers (Volvo/Mack, DDC, Cummins, International). Miller-type intake valve timing was the alternative technology to EGR use in Caterpillar.
Euro IV	2005	NOx = 3.5 g/kWh	EGR introduced by some manufacturers of heavy-duty truck and bus engines (Scania, MAN), urea-SCR in new competitive technology used.
Japan	2005	NOx = 2.0 g/kWh	EGR introduced by some manufacturers of heavy-duty truck and bus engines (Hino, Isuzu); used in competition to urea-SCR technology.
US	2007	NOx ≈ 1 g/bhp-hr	EGR used on heavy-duty truck and bus engines by all manufacturers.
Euro V	2008	NOx = 2 g/kWh	EGR continues to be used in some products by several OEMs (Scania and MAN), however, no OEM relies solely on EGR. Urea-SCR is still the competing technology.
US	2010	NOx = 0.2 g/bhp-hr	EGR combined with NOx credits allows one heavy-duty diesel engine manufacturer (Navistar) to certify engines to a 0.5 g/bhp-hr NOx level. All other manufacturers rely on a combination of EGR and urea-SCR.
Euro VI	2013	NOx = 0.4 g/kWh	Most manufacturers intend to use a combination of EGR and urea-SCR. The competing technology is urea-SCR without EGR (Iveco).
Type of vehicles : Non road engines			
US Tier 3	2006	NOx = 4.0 g/kWh	Cooled EGR engines introduced by John Deere. A number of other manufacturers used internal EGR.
US Tier 4i /EU Stage IIIB	2011	NOx ≈ 2 g/kWh	Cooled EGR introduced by a number of non road engine manufacturers; used in competition to urea-SCR technology.
IMO Tier III	2016	NOx = 3.4 to 1.96 g/kWh	EGR will be used in some two-stroke low-speed marine diesel engine applications (MAN Diesel & Turbo). Ammonia-SCR is an important competing technology.

Above table shows the use of EGR (hot and cold) combined other techniques in various types of engines to meet various emission standards limits [14]. Excluding these technologies there are other many ways suggested to control emissions. Various post treatment methods have been proposed to decrease tailpipe emission are Diesel particulate filters, Urea SCR, Diesel oxidation catalysts, and Lean NOx traps [15, 16]. These post treatment systems provide realistic solutions to meet the emission requirements, but these technologies add to production and operation cost. DPFs need periodically regeneration to meet emission requirements which increase fuel consumption and control complexity. LNT's use expensive platinum alloys as a catalyst, which significantly increase the capital cost [17]. Urea SCR required a second fluid filled in vehicle [18].

Due to problems of global warming and increased air pollution it must be assumed that the legislation emissions level may be further reduced. The effectiveness of emission reduction via engine based or post treatment will need to be evaluated once more by keeping in mind the fuel economy of engines [19]. Thus a primary target to next generation IC engine to decrease engine out pollution emissions by keep in mind all the aspects regarding cost and efficiency. The techniques presented in this paper go some way towards supporting this evaluation.

3. Review of different technologies and their effects:

Exhaust emissions can be lowered by reducing engine-out emissions through improvements to the combustion process and fuel management, or by changes to the type of fuel or its composition. Emissions control systems – EGR, Auto catalysts, Absorbers and Particulate filters – in combination with good quality fuel (low sulfur content) and enhanced engine management reduce emissions to very low levels. Here we elaborate the effect of some pre and post emission control technologies on engine emission and efficiency.

EGR concept:

Exhaust gas recirculation is the techniques in which a portion of engine exhaust is recirculate again into the engine inlet. This method is primarily used to reduce NOx, a harmful content of exhaust emissions. EGR working on the principle to reduce combustion chamber temperature because NOx is produced when temperature in the combustion chamber going above 2000 K. Exhaust consists of CO_2, N_2 and water vapors mainly, when some amount of this exhaust gas is entered with inlet fresh air it dilute the fresh air and reduces the O_2 concentration. Secondly exhaust gases have high specific heat that leads to decrease the combustion chamber temperature for same heat release. Hence EGR helps to reduction of combustion chamber temperature and step down NOx formation. EGR is used in IC engines from many years but now days this concept is became advanced and combined with other latest techniques to reduce emission levels. EGR is used in many different ways like Hot EGR, Cold EGR Low pressure EGR and High pressure EGR according to different required conditions. In literature various experiments was conducted to see the effects of EGR on engine performance parameters and emissions.

Experiment was conducted by P. Saichaitanya et al on a 4 stroke diesel engine by using both hot and cold EGR and the results shows that when 15% cold EGR is used it results in optimum engine performance [20]. Presently in new concepts of EGR the exhaust gas is firstly passes through filters to stop entering of PM of exhaust into combustion chamber and this will results into more advantages results.

Experiments conducted by K. Venkateswarlu et al by using hot EGR along with cetane improver shows a significant effect on NOx emissions [21]. Test results conclude that the brake thermal efficiency increases with the increase in the percentage of EGR which is accompanied by a reduction in brake specific fuel consumption and exhaust gas temperatures. There was reduction in NOx by 33% using EGR. Experiment was conducted by Nidal H. Abu-Hamdeh et al on the cold EGR shows a large decrease in the emission contents of pollution [22]. In the experiment he uses two types of fins solid and hollow. Firstly the air is passing through hollow fins to cool exhaust gas and then use water to circulate through fins to cool the exhaust. In this experiment results shows that there is decrease in NOx and CO_2 but increase in CO contents of exhaust. Final results show that when water is flowing through fins it leads to more decrease in temperature of exhaust and pollutants as compared to air flow through fins.

Advance fuel injection strategy:

We know the reduction of NOx is possible if we reduce the combustion chamber temperature. EGR is mostly used for this to reduce NOx emission. But high EGR rate effects the engine performance and increase soot concentration in the exhaust. Therefore use of EGR is limited by many factors and other effective methods are searched to reduce emissions. Advance fuel injection strategy used as effective technique to reduce combustion temperature and hence reduce emissions. Experiments was conducted by Julian T. Kashdan et al. [23] on a single cylinder all metal engine and an equivalent optical accessible version of same engine. The experimental study result shows the control of combustion temperature is possible by using advance fuel injection. Variation in injection rate has a significant effect on fuel mixture distribution and so heat release rate. It will result to decrease combustion temperature and noise. It effect to reduce HC and CO emission and we say that optimised fuel injection strategy will leads to decrease noise and engine emissions.

Another experiment carried out by Usman Asad et al. on a 4-cylinder Ford common-rail diesel engine running in a single cylinder mode for conducting tests [24]. In this experiment the effect of single shot versus 2 shot fuel injection strategy was studied. The use of 2-injection strategy helps to significantly reduce the NOx emissions but more amount of soot is produced as compared to single injection strategy. The results shows two-injection strategy is very effective in conventional HTC engines and target emissions limit are achieved by using multi-injection strategy.

Late Intake Valve Closing:

LIVC is another pre treatment technique that shows considerate effects in the reduction of pollutant contents of exhaust. In this method inlet valve is remain open for more time than in conventional engines. Compression starts only after the inlet valve is closed, so as the piston moves upward it expels some amount of charge back. Compression occurs during latest part of compression stroke, here LIVC leads to decrease in compression ratio and hence decrease the combustion chamber's temperature. It longer the ignition delay time and a subsequent reduction in local fuel rich combustion zones. It gives more time to the mixing of fuel and air before start of ignition. This phenomenon leads to reduction of NOx and PM. Experiment shows that up to 95% PM reduction is possible at some operating conditions. It also helps to reduce combustion noise at both low and medium loads due to slow heat release. LIVC helps to expand early premixed charge compression ignition operation to higher load range, secondly it reduces CO emission and improves combustion efficiency at low loads by optimizing the fuel injection timing. Experiment conduct by Xin He et al shows about 30-50% NOx reduction is achieved in this technique by fixing combustion phase and optimizing fuel injection [25]. With LIVC, EGR requirement reduced by 25-30% at low loads and 15% at high loads. LIVC technique reduces the soot emission for al operating conditions. LIVC is also results in some losses that it reduces the volumetric efficiency of engine. However, it may not be a problem, even the air fuel ratio can reduce but it provides enough air to reach stoichiometric ratio for achieving good combustion quality.

Effects of ignition delay:

Ignition delay is an effective method to reduce emissions, with ignition delay more time is available for premixing that leads to proper combustion of fuel. The experiment is conducted by Mohan K.Bobba et al. [26] on a heavy duty diesel engine using an electronically controlled common rail fuel injector. This injector used a solenoid actuator pilot valve and a pressure balanced needle to control fuel delivery. Here engine is operating at low temperature combustion conditions with 12.7% intake oxygen concentration. The intake engine temperature is varied to achieve different ignition delays, while adjusting the intake pressure to keep the TDC charge density constant. Spatial and temporal evolution of soot in the engine was studied using two color soot thermometry and high speed soot luminosity imaging as the ignition delay was varied. The two color measurements shows reduced soot formation for low temperature conditions. As the ignition delay increase, enhanced mixing at the end of injection gradually spreads downstream, preventing soot formation near injector. Results shows ignition delay is an effective method to enhance emissions by little effecting engine performance.

PCCI:

CI engines are highly efficient, in CI engines combustion starts as the fuel injected when piston is at TDC. High compressed air immediately auto ignites as the fuel is sprayed on it. In conventional engines a very less time is available to premix fuel and combustion chamber oxygen it leads to formation of high soot and NOx at the exhaust end. So it is need to increase time for better mixing of fuel and oxygen. PCCI combustion is a practical way to increase fuel air mixing time and it helps decrease NOx and PM contents in CI engines. In PCCI combustion higher amount of cooled EGR is used to decrease the peak prolong delay. EGR is effective way to control NOx but tradeoff in terms of HC and PM emission is also high. In PCCI the complete earlier and ignition delay is increased. This method helps to a great reduction of NOx due to decrease in combustion temperature.

Review studies suggest that fuel can be injected into combustion chamber through port fuel injection, early direct injection and by late direct injection techniques [27, 28]. First two methods not preferred, here the fuel impinges on cylinder walls and not fully vaporized that causes increase in CO, UHC emissions. Narrow spray cone injectors are used use to reduce fuel impinges on cylinder walls. Late direct injection is the good strategy to improve the above methods limitation and to reduce emissions.

Varying compression ratio:

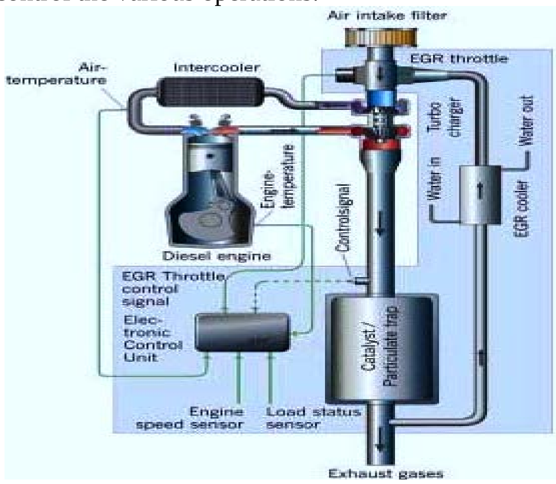
By lowering compression ratio vehicle can burn unleaded fuel. The use of unleaded fuel enhances the performance of catalytic converters and helps to reduce HC and CO emissions. Lower compression ratio also leads to decrease combustion temperature and hence reducing NOx emission. Studies will be carried out regarding the effect of compression ratio on the performance and emissions of diesel engines [29]. Experiments observation shows that by increasing the compression ratio, brake specific fuel consumption will decrease, whereas thermal Efficiency and exhaust gas temperature increases. By reducing the compression ratio, it is observed that there will be reduction in NOx and PM but simultaneously a small increase in CO and HC emissions. Low compression ratio helps to decrease emissions but it also causes some problems related to engine cold start ability and efficiency. The way suggested to reduce these negative effects is to make a bowl in piston to reduce CR.

In case of SI engines with EGR the losses in engine performance is easily recovered by increasing the compression ratio [30]. Small amount of EGR recirculation is enough to keep emissions down to an acceptable level. Increasing the compression ratio from 8.2:1 to 8.9:1, with 6% recirculation ratio leaded to a 50% reduction in the emission of NO_x and 10% increase in power output of the engine.

Catalytic convertors and other post treatment techniques:

A Catalyst is a material that can speed up chemical action without changing itself. Catalyst-equipped cars were first introduced in the USA in 1974 but successfully appeared on European roads in 1985. After the year of 1993 European Union set new car emission standards where it makes necessary to use catalysts in gasoline fuelled cars to control emissions. After the mid 70s mostly automotive manufacture starts installing catalytic convertors because of its successful results to control emissions in SI engines. Catalytic converters used in automobiles are of two types two way and three way catalysts. These and made of platinum, palladium and rhodium or a combination of these materials. Two way catalytic converters only convert HC and CO and NOx is not converted. These are coated with platinum and referred to as oxidation converters [31]. Three way catalytic converters can convert all three exhaust gasses HC, CO, NOx. Presently cerium is

used in new catalytic convertors, it release oxygen to increase the rate of change HC and CO into CO2 and Water.
Catalytic convertors efficiency decreases at low temperature, so in CI engines because of the lower temperature exhaust gases of engine (larger expansion ratio) they not showing successful results to reduce emissions. Platinum and palladium are two main catalyst materials used for catalytic converters on CI engines. They promote the removal of 30-80% of the gaseous HC and 40-90% of the CO in the exhaust. The catalysts have little effect on solid carbon soot but do remove 30-60% of the total particulate mass by oxidizing a large percent of the HC absorbed on the carbon particles. Diesel fuel contains sulphur impurities, and this leads to poisoning of the catalyst materials. However, this problem is being reduced as legal levels of sulphur in diesel fuels continue to be lowered.
In CI engines particular traps are used in the exhaust flow line to decrease the amount of particulates from exhaust. These particular traps are like filters and made of ceramics in form of wire mesh, a monolith. Traps show successful results to remove about 60-90% of exhaust particulates. As they are work as filters so after long time of use they slowly filled up with the PM. They restricts the exhaust gas flow and increase the back pressure of engine and this leads to temperature rise of exhaust and increase in fuel consumption. It is need to regenerate particulate traps when they choked or saturated. Sensors are used to sense pressure drop in exhaust line as pressure decrease due to more restriction by particulates in exhaust pipe. Radio signals are used to sense amount of particulate collected in pipe (radio wave absorption increase as the amount of particulate increases) [32]. Another new effective technique is **Selective Catalytic Reduction** (SCR) where a liquid-reductant agent through a special catalyst enters into the exhaust stream of a diesel engine. Selective word is used because it controls the emission of NOx only. The reductant agent is usually automotive-grade urea, also known as Diesel Exhaust Fluid (DEF). The DEF sets off a chemical reaction that converts nitrogen oxides into nitrogen, water and tiny amounts of carbon dioxide (CO2) that are not harmful [33].The chemical reaction is known as "reduction" where the DEF is the reducing agent that reacts with NOx to convert the pollutants into nitrogen, water and tiny amounts of CO2. The DEF can be rapidly broken down to produce the oxidizing ammonia 6. There are a number of additives, which are added in order to reduce the smoke from CI engine. HYDRAX ATH (hydrated alumina), HYDRAMAX (magnesium hydroxides and hydroxyl-carbonates), CHARMAX LS (low smoke), CHARMAX LS ZST & LS ZHS (zinc stannates & zinc hydroxystannates), CHARMAX AOM & MO (ammonium octamolybdate & molybdic oxide),CHARMAX ZB200 & ZB400 (zinc, magnesium, and calcium borates) etc. These reduce the amount of smoke produced by various chemical reactions. These post treatment techniques are successfully implemented in new IC engines and gave satisfactory results to meet new emission norms.
Figure (1) shows the combined techniques used in new IC engines with electronically control system to control the various operations.



Water injection technique:
Water has been added to the high performance, reciprocating aero SI engines during Second World War to suppress engine knock. Water addition to intake charge has been investigated by many researchers to reduce NOx formation. The main pollutant contents emitted by any IC engine vary in their amount according to different running conditions of engine. The reasons behind the production of these unwanted contents are mainly high combustion temperature and incomplete combustion. The methods that help to decrease combustion chamber temperature will also lead to reduce emission pollutant contents. The introduction of water by the emulsification process significantly effects the combustion process that have direct consequences on the pollutant formation. Vaporization of water due to heat absorption from its surroundings will lower the local high temperature resulting in the reduction of emissions [34, 35, 36]. Diesel-water emulsion as alternative fuel has potential to significantly reduce the formation of NOx and PM in the diesel engine. The emulsion fuel contains water (in the range of 5–15%) and diesel fuel with specific surfactants, to stabilize the system [35].
Experiment was conducted by Hrishikesh Sane et al. in a laboratory installed diesel engine coupled with an eddy current dynamometer [38]. The emission and performance characteristics are compared when same engine worked with pure diesel and when it use

diesel emulsion as a fuel. The result shows that BSFC decreases when emulsion used instead of diesel. It decreases up to a limit and then increases. The BSFC is best obtained when 7.5% of water in used in emulsion. With increasing in load on engine CO and NOx emissions both increases, but when emulsion used due to decrease in temperature of combustion chamber and incomplete combustion CO emissions increase at high rate but NOx level is comparatively reduces. Experiment investigation in literature shows that 10% and 25% reduction of emissions in a single cylinder diesel engine for 10% and 20% water in the emulsion was observed.

Prof. Dr. Eng. Dan Scarpete et al. [39] suggested four methods to enter water into combustion chamber: (i) Direct injection into the engine through separate injectors (DWSI); (ii) Hybrid injection, using a single injector or as a stratified diesel-water-diesel fuel injection by means of a specially modified nozzle (HDWI); (iii) Fumigating the water into the engine intake air (FWIA); (iv) Diesel-water emulsions (DWE). The last technique diesel oil emulsion suggested to best. The results of experiment shows the engine power decreases with water emulsion due to lower heating value of emulsion compared to pure diesel fuel. The pollutant contents NOx and smoke emissions tend to decrease as the emulsion ratio increases due to the lower peak temperature in cylinder due to the water content in emulsion fuel and enhanced mixing with air by micro-explosions.

Experiment was conducted by Juhi Sharaf et al. on SI engines [40]. Water has been directly injected into intake manifold or used as water-fuel emulsion. Emulsifying chemicals in about 2 per cent by volume are added to form water-gasoline emulsions. Result shows that with water addition ranging from 10 to 30% by volume of gasoline, large reductions in NOx are possible but it leads to increase in amount HC and a slight increase in CO occurs. A small improvement in BSFC with small addition of water is observed but the BSFC increases with higher amounts of water addition. The stability of emulsion may be around a few days and the addition of emulsifiers usually reduces the fuel octane number. This approach is not successful to practically use as long time strategy in large scale due to harmful effects of water addition as HC and BSFC increase, and corrosion of engine components is also encountered. But the experiments conducted by various researcher shows that water-oil emulsion may be used as an effective technique to reduce emission when used under proper controlled conditions.

Conclusion:

In this review paper we discuss about different types of conventional and non-conventional techniques. All the above methods EGR, LIVC, Water injection, Advance fuel injection, Catalytic convertors, DPF's, NOx traps helps to reduce emissions and some techniques like EGR and Catalytic convertors show more consistent effect to reduce emissions. Every technique has some limitations also in form of decrease in engine efficiency, installation feasibility and cost factors. It is not possible that any technique if separately used able to produce highly efficient and clean exhaust engines to fulfill new emission norms, so it is need to combine two or more techniques. Presently in new engines EGR is effectively used with other post treatment methods like Urea SCR, DPF and catalytic convertors to fulfill new emission legislations. The objective is to establish next generation highly efficient and clean exhaust engines so the emissions can be reduced to estimated levels required by the next emissions target 'Euro 6' standards.

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