A review of Hot and Cold Exhaust Gas Recirculation (EGR) in Compression Ignition Engine

[1]Nirav Joshi, [2]Dr N M Bhatt

[1]Research scholar, [2]Director, Gandhinagar Institute of Technology
[1]Mechanical Engineering Department,
[1]Gujarat Technological University, Ahmedabad, Gujarat, India.

Abstract : In current time, majority of the transport vehicles in developing countries like India where cost effective and for this, the predominant criteria utilize diesel engines rather than petrol engines. Usage of diesel engines was rapid since last few years which can be addressed from the sales report of many automobile companies. The reason behind this could be cost of diesel fuel and efficiency of the diesel engine when compared to petrol engine. On the other side, the main problems associated with diesel engine is the formation of high levels of NO_X, which is a temperature-dependent phenomenon. It is compulsory to address this emission problem and in order to reduce NO_X emissions from the engine, it is necessary to keep peak combustion temperatures under control. This critical review on the effect of Exhaust Gas Re-circulation (EGR) on the exhaust gas temperatures, NO_X emissions, efficiency and other parameters. The exhaust gas temperature, NO_X & hydrocarbon emissions and efficiency were compared for different percentages of hot and cold EGR for diesel. The EGR system was a very effective way for reducing NOx emission from a diesel engine, particularly at the high load of engine operation condition.

IndexTerms **- Diesel Engine, Emission, NO_X, EGR.**

Nomenclature

CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
EGR	exhaust gas recirculation
HC	hydrocarbon
NOx	oxides of nitrogen
PM	particulate matter

1. INTRODUCTION

Over recent past years, stringent emission legislations have been imposed on NOx, smoke and particulates emitted from automotive diesel engines worldwide. Diesel engines are typically characterized by low fuel consumption and very low CO emissions. However, the NOx emissions from diesel engines remain high. Hence, in order to meet the environmental legislations, it is highly desirable to reduce the amount of NO_X in the exhaust gas.

We all know the CI engines are widely used because of its high thermal efficiency and low maintenance [1]. It runs on diesel fuel which is a conventional fossil fuel and is on the verge of extinction. Also exhaust gas (HC, CO, CO_2, NOx etc) of diesel engine are very harmful and major source of air pollution hence contributing to global warming. Studies have found that over 60% of the total air pollution is caused by engine exhaust. Engineers and scientists have done lots of research and experiments to finding alternative for diesel engine and effective means to control emission which is contributing to air pollution. They found that biodiesel as a fuel can replace diesel and it can reduce the harmful exhaust gases to significant amount. However, people are still working in this field to find the best alternative for diesel fuel. Biofuel (biodiesel) have potential to meet the growing energy demand for this world in sustainable manner.

1.1 Exhaust Gas Recirculation (EGR)

In Exhaust Gae Recirculation (EGR) technique, the part of exhaust gases are being recirculated which aids in reducing the NO_X emission as shon in fig. 1. Exhaust gases normally contains of CO_2, NO_X etc and mixture has higher specific heat compare to atmospheric air, thus recalculated exhaust gases displace fresh air in combustion chamber and hence, it helps to reduce oxygen available for combustion and also it increase the specific heat of mixture entering the combustion chamber thus lower flame temperature.

EGR is one of the most effective and economical method to reduce NO_X emission. EGR helps in increasing the heat capacity, dilution of intake charge and ignition delay. Dilution theory says that, effect of EGR on NO_X is caused by increasing amount of inert gas in the mixture reduces the adiabatic flame temperature.

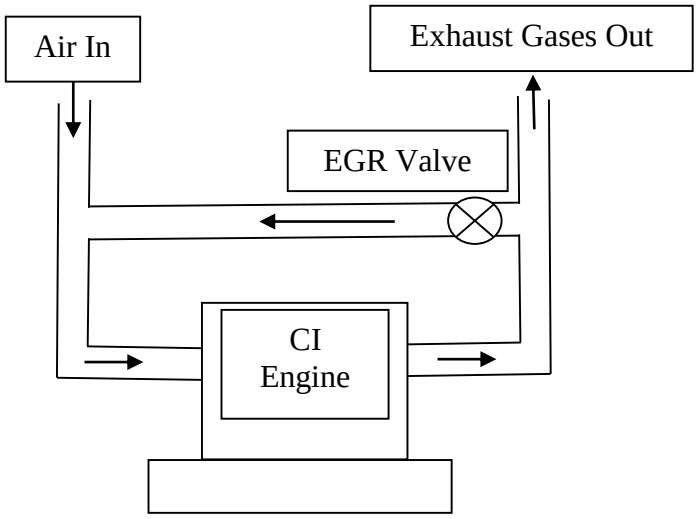

Fig. 1 Exhaust gas recirculation

EGR is a useful method for reducing NOx formation. Exhaust consists of CO_2, N_2 and water vapor mainly. When a part of this exhaust gas is recirculated to the combustion cylinder, it acts as diluents. This also reduces the O_2 concentration in the combustion chamber. But it was found that biodiesel fuel has higher NOx emission than pure diesel operated engine. Also many researches in total ambiguity to concentrate on blend concentration and finalization of engine parameters [2] and to fight food to fuel crises [3] NOx emission cannot be eliminated completely but it can be reduce to considerable amount with the help of exhaust gas recirculation (EGR).The specific heat of the EGR is much higher than fresh air hence EGR increases the heat capacity of the intake charge, thus decreasing the temperature rise for the same heat release.

$$\%EGR = \frac{\text{Volume of EGR}}{\text{Total charge intake into the cylinder}} \text{ X } 100$$

Another way to define the EGR ratio is by the use of CO_2 concentration:

$$\text{EGR ratio} = \frac{[CO_2]_{intake} - [CO_2]_{ambient}}{[CO_2]_{exhaust} - [CO_2]_{ambient}}$$

1.2 EGR Classified based on temperature

1. Hot EGR: Exhaust gas is re-circulated without being cooled, resulting in the increased charge temperature.

2. Fully cooled EGR: Exhaust gas is cooled before re-circulation into the combustion chamber by the means of a water-cooled heat exchanger. In this case, condensed water enters the cylinder and produces undesirable effects.

3. Partly cooled EGR: To avoid the water condensation, the temperature of exhaust gas is kept just above its dew point temperature.

In case of hot EGR, thermal efficiency is found to improve due to increased intake charge temperatures and re-burning of the unburned fuel present in the re-circulated gas. Therefore, it has been concluded that the use of EGR is most effective in improving exhaust emissions at low loads. In cooled EGR the condensed water is removed before mixing with fresh air. This minimizes the effect of water on soot and oxidation kinetics inside the combustion chamber. The use of EGR is suggested as a method of improving the engine performance and reducing the emissions of diesel engines. By increasing the intake charge temperature, EGR could promote better combustion. Some of the unburned fuel can be reburned with this method. The use of EGR is a promising method for improving part load operation and reducing the exhaust NOx emissions. However, when EGR is used it will change the rate of combustion or the rate of pressure rise inside the combustion chamber. There is trade-off between NOx emission hence as the EGR rate increases, the level of NOx goes down.

The purpose of the EGR system is to precisely regulate EGR flow under different operating conditions, and to override flow under conditions which would compromise good engine performance. It was found from fig. 2 that adding EGR to the air flow rate to the Diesel engine, rather than displacing some of the inlet air, appears to be a more beneficial way of utilizing EGR in Diesel engines. About 15% recycle will reduce NOx emission by about 80%.

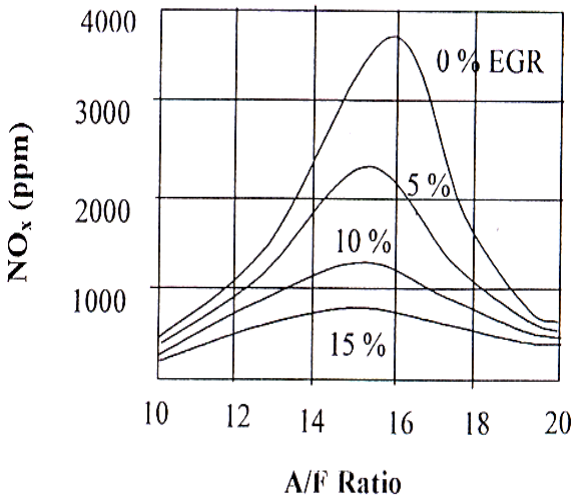

Fig. 2 Effect of EGR on NO_X emission.

2. Literature Survey

Daiso *et al* [6] carried out experimental investigations on a direct-injection diesel engine dual-fuelled with natural gas by implementing all three above-mentioned EGR methods. They found that:

1. At lower loads using hot EGR, brake thermal efficiency is improved due to increased intake temperatures. Also NOx and smoke emissions come down. Cooled EGR gives relatively lower thermal efficiency but lower NOx emissions also.
2. At high loads fully cooled and partly cooled EGR tends to significant reduction in NOx and smoke emissions due to delay in dual-fueled combustion. Partly cooled EGR is found to be a better solution as it prevents the water condensation. At lower loads, high unburnt hydrocarbon emissions are observed. Sometimes a suitable oxidation catalyst is used (Pt or Pd) in the catalytic converter for improving the combustion of after treatment exhaust gas.

Pratik G. Sapre et al. [7] have investigated various exhaust gas recirculation rates on engine emission characteristics like NOx, HC, CO, CO_2, exhaust gas temperature. They evaluated experimentally on a single cylinder, naturally aspirated 4-stroke, vertical air-cooled CI engine. Readings were recorded on the following torque ratios 5, 10, 15, 20, 25, 30, 35, 40, 45 N-m and varying EGR.

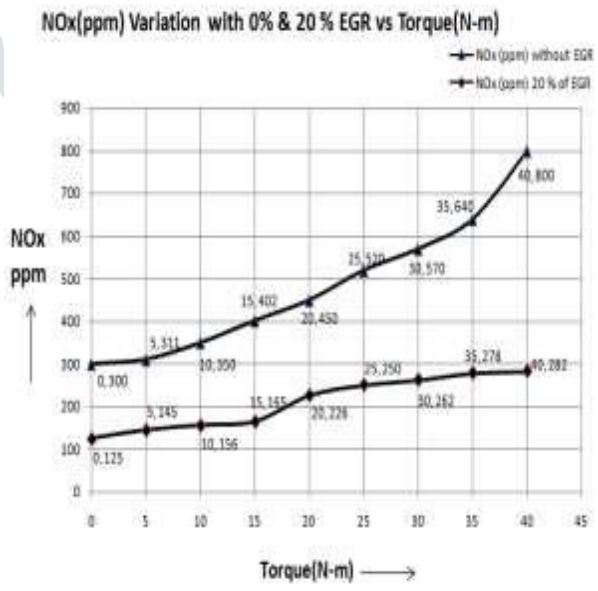

Fig. 3 NO_X Vs. Torque (N-m) variation curve

Fig. 3 shows comparison graph of with and without EGR system of variation in Emission of NOx with respect to engine Torque(N-m).From respective figure it is clear that the value of Emission of NOx of diesel engine with EGR system is much less than that of engine running on without EGR system.

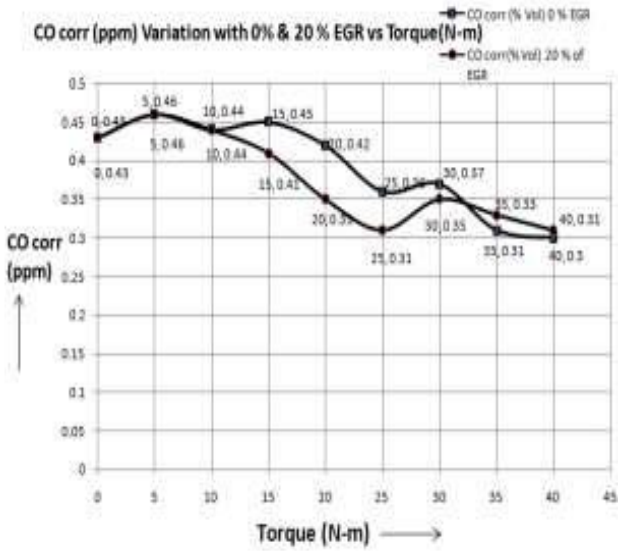

Fig. 4 CO corr Vs. Torque variation curve

Fig. 4 shows comparison graph of with and without EGR system of variation in emission of CO with respect to engine Torque (N-m). Fig. 5 shows comparison graph of with and without EGR system of variation in emission of HC with respect to engine Torque (N-m). In Above graph, NOx as well as CO_2 is having directly proportional relationship.

They found that NOx emission got reduced to 64.75% and HC emission increased with EGR mode but HC emission was observed less with non EGR. They concluded that 20% of EGR was optimum for NOx reduction without significant penalty on brake specific fuel consumption and HC emission.

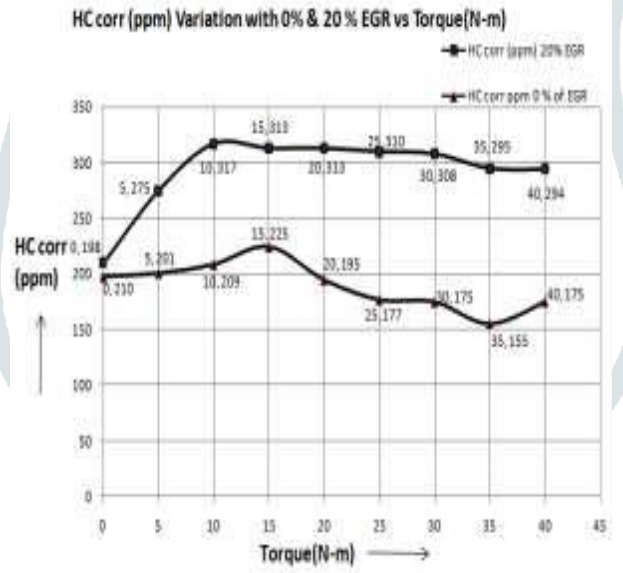

Fig. 5 HC corr (ppm) Vs. Torque (N-m) variation curve

R.Senthilkumar et al. [1] have performed experiment to study the effect of hot and cold exhaust gas recirculation (EGR) methods on emission and efficiency of diesel engine. They have conducted experiment on single cylinder, 4-stroke, water cooled, direct injection diesel engine. The tests are conducted at rated speed of 1500 rpm and at various loads. They used heat exchanger for obtaining different EGR methods. They have carried out experiment with and without EGR having 10%, 15% and 20% of EGR. They observed that specific fuel consumption was noted high at all loads with and without EGR, brake thermal efficiency with 10% EGR was comparable without EGR at all loads. They also investigated that indicated thermal efficiency for cold EGR (water cooled) was found to be better in comparison with hot EGR and intermediate EGR, but it relatively low without EGR. Oxides of Nitogen (NOx) emittent coming out from the test rig using hot EGR is comparatively higher than without EGR and Cold EGR of higher rates shows much effective in reducing NOx emission. And CO emissions with EGR were increased in part loads and decrease with higher loads as compare without EGR.

E. Kazuya Ishiki, et.al. [9] studied on the mechanism of wear induced by soot in the EGR gas. The piston ring of the test engine was chrome plated and the cylinder was made of boron steadite cast iron. Detailed observations of the ring sliding surfaces and that of the wear debris contained in lubricating oil were carried out. It was found that the wear of the top ring sliding surfaces identify abrasive wear without respect to the presence of EGR by steadite on the cylinder liner sliding surface. In addition, it was confirmed in a cutting test that soot mixed lubricating oil improved in performance as cutting oil. Based on these results, it was proposed that the ring wear is accelerated at EGR because abrasive wear increases due to a lot of soot mixed into lubricating oil improving the performance of lubricating oil as cutting oil.

Nidal H. Abu-Hamdeh [10] carried out a study on spiral fin exhaust pipes, to determine the effect of cold EGR on the chemical composition of the exhaust gases and the reduction in the percentages of pollutant emissions in diesel engines. The gases examined in this study were oxides of nitrogen (NOx), carbon dioxide (CO_2) and carbon monoxide (CO). In addition, O_2 concentration in the exhaust was measured. The two designs adopted in this study were exhaust pipes with solid and hollow fins around them. The first type uses air flow around the fins to cool the exhaust gases. The second type consists of hollow fins around the exhaust pipe to allow cooling water to flow in the hollow passage. Different combinations and arrangements of the solid and hollow fins exhaust pipes were used. It was found that decreasing the temperature of the EGR resulted in reductions in the oxides of nitrogen (NOx) and carbon dioxide (CO_2) but increased the carbon monoxide (CO) in the exhaust gases. In addition, the oxygen (O_2) concentration in the exhaust was decreased. As a general trend, the percentages of reduction in the NOx gas concentrations were lower than the percentages of increase in the CO emissions as a result of cooling the EGR of a diesel engine by a heat exchanger. Using water as a cooling medium decreased the exhaust gas temperature and pollutants more, than did air as a cooling medium. In a separate series of tests, it was observed that, increasing the cold EGR ratios decreased the exhaust NOx but increased the particulate matter concentrations in the exhaust gases.

K Srinivasa Rao et al. [11] performed experiments on single cylinder, direct injection, CI engine using waste cooking oil methyl ester blends with varying EGR rates of 0%, 5%, 10%, 15% and 20%. They stated that the brake thermal efficiency of engine increases till 15% of EGR and reduces with further increase in EGR percentage. The unburned hydrocarbon emission was observed low at lower EGR rates. Lowest BSFC was obtained at 15% EGR. It is observed that the NO_X emissions were reduced for all blends using Exhaust Gas Recirculation technique. For all blends at 15% EGR rate, the engine characteristics were phenomenal.

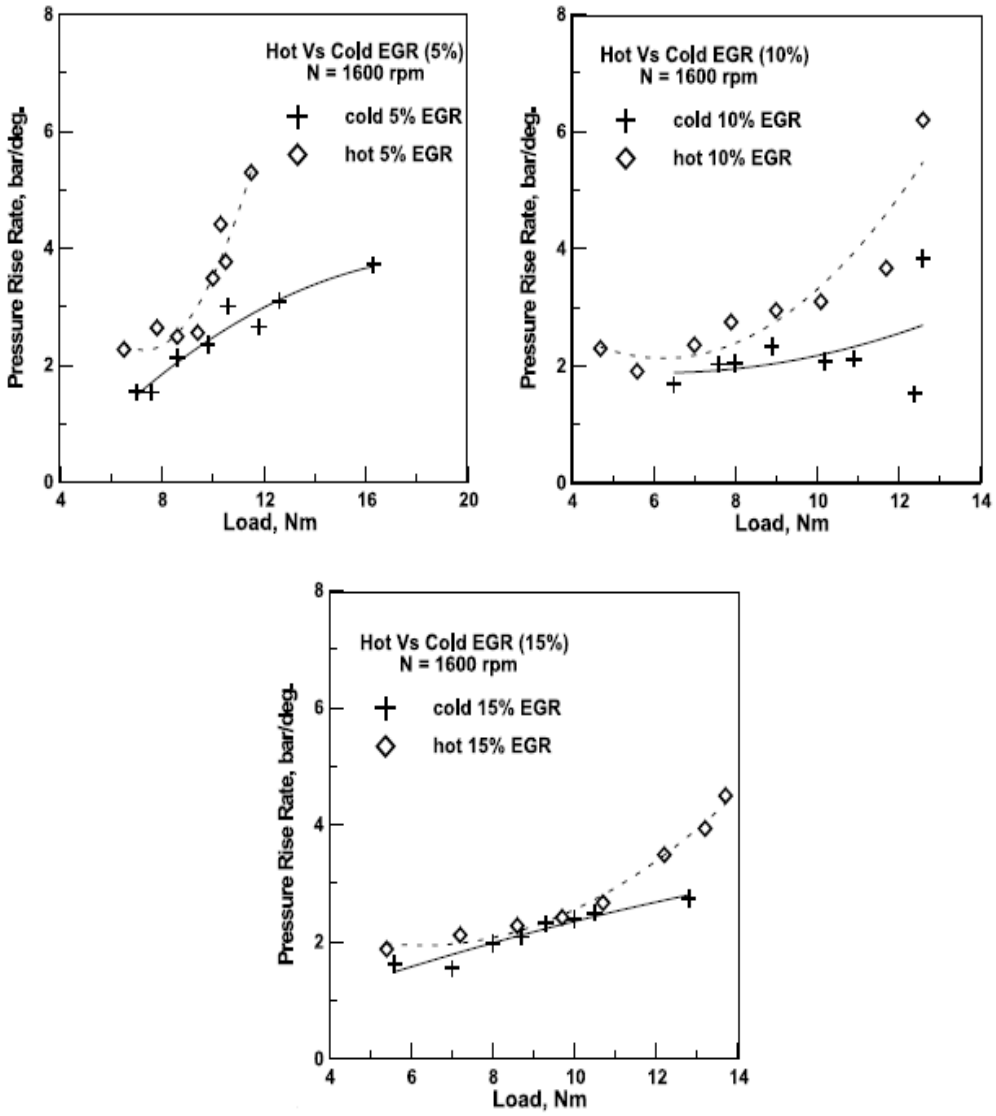

Fig. 6 Effect of load on maximum pressure rise rate for hot and cold EGR.

Mohamed Y.E. Selim [8] studied the effects of EGR ratio, engine speeds, loads, temperature of recycled exhaust gases, intake charge pressure and engine compression ratio on combustion noise and thermal efficiency and observed that Exhaust gas recirculation at an EGR ratio of 5 % has a positive effect on increasing the thermal efficiency. The use of a low EGR ratio of 5% is also favourable for reduced combustion noise and reduced NOx emission. The effect of intake charge pressure on maximum pressure rise rate may be seen in Fig. 6. The test was performed at 0% EGR, since EGR gases could not be used for the higher intake charge pressure. However, increasing the EGR reduces the thermal efficiency. The hot EGR increases the pressure rise rate at all loads and at all EGR ratios used as compared with cooled EGR.

Shaik Khader Basha et al [12] presented in their technical paper the effects of hot and cold Exhaust gas recirculation (EGR) methods on emissions and efficiency of the single cylinder, 4-stroke, direct injection diesel engine. For getting different EGR methods heat exchanger is provided. With and without Exhaust gas recirculation the performance characteristics like efficiencies, emissions were studied. In this project the different amounts of EGR like 10%, 15% and 20% of EGR is used to study the effects on the performance characteristics The recirculation of exhaust gas reduces the oxygen quantity in the combustion chamber and increases the temperature of intake charge which reduces the flame temperature and makes to lower NOx formation. By increasing the cooled EGR rates reduces the emissions more effectively.

A. Mohebbi et al [13] presented in their technical paper nitrogen oxides influence of EGR on diesel engine combustion, NOx/PM emissions, brake specific fuel consumption (BSFC), engine thermal efficiency, cylinder pressure and heat release rate (HRR) are analysed and presented. The experiments have been conducted on a turbocharged DI diesel engine under full load condition at two different injection timings in order to distinguish and quantify some effects of Hot and Cooled EGR with various rates on the engine parameters. Experimental results showed that increase of EGR rate has a negative effect on air-fuel ratio. For a premixed combustion at constant boost pressure, ignition delay is increased leading to retardation of all combustion process, a low HRR peak and reduce of in-cylinder peak temperature. Using of Hot EGR reduces NOX emissions whereas PM emissions are increased. The advance of injection timing resulted in the reduction PM while both NOX emissions and fuel consumption were increased. The use of cooled EGR was more effective compared to the hot EGR. As a result, the EGR temperature has no significant impact on NOx emissions. With increasing EGR rate, unequal EGR distribution was increased in inlet port of cylinders while the reducing EGR temperature (cooled EGR) improved its distribution among the engine cylinders and decreased the EGR cylinder-to-cylinder variations.

3. Conclusion

The effect of EGR can be found predominant in reduction of NO_X emissions. When in comparison between the hot EGR and cold EGR, Cold EGR has the greater advantage if is well designed. There is a slight increase in efficiency of engine due to EGR. When the biodiesel is used as fuel, there is a problem with increase in NO_X emissions as well as there will be reduction in performance of the engine. But if EGR technique is incorporated with the biodiesel, then there will be greater advantage of increasing the performance of engine as well as reduction in all the emissions. Smoke increases slightly with increase in percentage of EGR. Experimental results show that the cold EGR is much effective than the hot and intermediate EGR for the reduction of NOx emission. The increase in temperature of EGR gases causes to increase the combustion temperature which leads to increase in formation of NOx. The Volumetric efficiency was almost same in all the cases and the brake specific fuel consumption was 7% lower with 22.65% of EGR

So, taking all the results into consideration from the present experiment, Cold EGR with 15% exhaust gas recirculation would result in optimum engine performance as well as reduction of emissions.

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