Review on Effect of Exhaust Gas Recirculation (EGR) on Performance and Emission of Diesel Engine

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Abstract— To meet stringent vehicular exhaust emission norms worldwide, several exhaust pre-treatment and post treatment techniques have been employed in modern engines. Exhaust Gas Recirculation (EGR) is a pretreatment technique, which is being used widely to reduce and control the oxides of nitrogen (NOx) emission from diesel engines Oxides of nitrogen (NOx) are formed during combustion inside cylinder which is responsible for major respiratory problems in human beings. NOx also contributes to global warming and acid rain formation. One of the techniques of reducing the oxides of nitrogen in the exhaust from the engine is to use exhaust gas recirculation (EGR) technique. This paper presents a brief review on the effect of exhaust gas recirculation (EGR) on engine performances and exhaust emission characteristics of compression ignition engines based on the reports of different researchers available in the literature.

Index Terms— Diesel engine, EGR, emission, NOx, pollution.

I. INTRODUCTION

Several exhaust pre-treatment and post treatment techniques have been employed in modern engines to overcome stringent vehicular exhaust emission (VEE) norms worldwide. Exhaust Gas Recirculation (EGR) is one pretreatment technique, which is being used widely to reduce and control the oxides of nitrogen (NOx) emission from diesel engines.

II. NO_x FORMATION MECHANISM

NO is formed inside the combustion chamber in post-flame combustion process in the high temperature region. The NO formation and decomposition inside the combustion chamber can be described by extended Zeldovich Mechanism [8]. The principal reactions at near stoichiometric fuel–air mixture governing the formation of NO from molecular nitrogen are:

$O + N_2 \rightarrow NO + N$

$N + O_2 \rightarrow NO + O$

$N + OH \rightarrow NO + H$

The initial rate controlled NO formation (i.e. when $[NO]/[NO_2]_e << 1$) can be described by the Eq. (1). In the expression, [NO] denotes the molar concentration of the species and $[O_2]_e$ and $[N_2]_e$ denotes the equilibrium concentration [7].

$$\frac{d[NO]}{dt} = \left(\frac{6\times10^{16}}{T^{0.5}}\right) \exp\left(\frac{-69{,}096}{T}\right) [O_2]_e^{0.5} [N_2]_e \ \text{mols/cm}^3. \quad (1)$$

The sensitivity of NO formation rate to temperature and oxygen concentration is evident from this equation. Hence in order to reduce the NOx formation inside the combustion chamber, the temperature and oxygen concentration in the combustion chamber need to be reduced. Even though, certain cetane improving additives are capable of reducing NOx, the amount of reduction is reported to be inadequate. Moreover, most of these additives are expensive. Retarded injection is an effective method employed in diesel engines for NOx control. However, this method leads to increased fuel consumption, reduced power, increased HC emissions and smoke. Water injection is another method for NOx control however this method enhances corrosion of vital engine components. In addition, it adds to the weight of the engine system because of requirement of a water storage tank. It is also difficult to retain water at a desired temperature during cold climate [9].

III. EXHAUST GAS RECIRCULATION

Exhaust Gas Recirculation is an effective method for NOx control. The exhaust gases mainly consist of carbon dioxide, nitrogen etc. and the mixture has higher specific heat compared to atmospheric air.

Re-circulated exhaust gas displaces fresh air entering the combustion chamber with carbon dioxide and water vapor present in engine exhaust. As a consequence of this air displacement, lower amount of oxygen in the intake mixture is available for combustion. Reduced oxygen available for combustion lowers the effective air–fuel ratio. This effective reduction in air–fuel ratio affects exhaust emissions substantially. In addition, mixing of exhaust gases with intake air increases specific heat of intake mixture, which results in the reduction of flame temperature. Thus combination of lower oxygen quantity in the intake air and reduced flame temperature reduces rate of NOx formation reactions[10,11]. The EGR (%) is defined as the mass percent of the recirculated exhaust (M_{EGR}) in the total intake mixture (Mi).

$$EGR(\%) = \frac{M_{EGR}}{M_i} \times 100$$

Desantes et al. used NDIR-based CO_2 concentration measurement at the intake ($[CO_2]int$) and exhaust manifold ($[CO_2]exh$) for the determination of EGR rate [12].

$$EGR = \frac{[CO_2]_{int} - [CO_2]_{atm}}{[CO_2]_{exh} - [CO_2]_{atm}}$$

The engines using EGR emit lower quantity of exhaust gases compared to non-EGR engines because part of the exhaust gas is re-circulated [13]. Thus even if the concentration of toxic substances in the exhaust gas remains unchanged, the total quantity of emission of toxic substances reduce for the same volumetric concentration. Diesel engines operating at low loads and generally tolerate a higher EGR ratio because re-circulating exhaust gases contain high concentration of oxygen and low concentration of carbon dioxide and water vapors. However at higher loads, the oxygen in exhaust gas becomes scarce and the inert constituents start dominating along with increased exhaust temperature. Thus, as load increases, diesel engines tend to generate more smoke because of reduced availability of oxygen [2].

IV. EFFECT OF EGR ON PERFORMANCE

The effects of both hot and cold Exhaust gas recirculation (EGR) methods are evaluated.

A. Effect on Specific Fuel Consumption and Thermal Efficiency

Based on their experimental work, Shaik Khader Basha et al [1] have been presented in graphical form in figure 1 and figure 2 respectively.

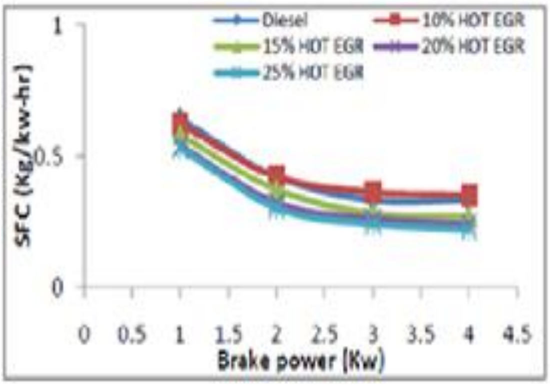

Figure 1: BP Vs SFC for various hot EGR ratios [1]

From the graphs, it is observed that Specific fuel consumption is found to be less at all loads for higher hot EGR Ratios compare to without EGR. Brake thermal efficiency with 10% EGR was comparable without EGR at all loads. Indicated thermal efficiency with cold EGR is found to be better as compared with hot and intermediate EGR but it relatively low without EGR.

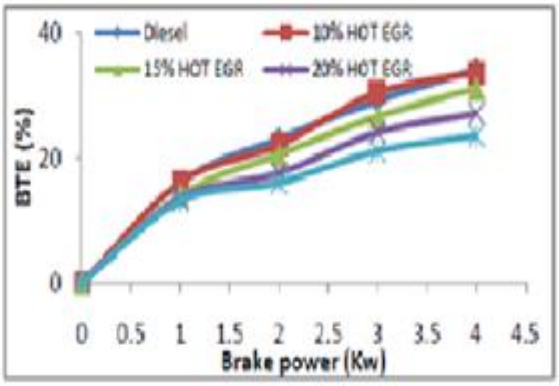

Figure 2: BP Vs BTE for various hot EGR ratios [2]

P. SaiChaitanya et al. [3] have been presented in graphical form in figure 3 and figure 4 respectively. From the graphs, it is observed that the brake thermal efficiency increases with the load and the maximum possible brake thermal efficiency will be at the maximum load. There is a slight increase in brake thermal efficiency as the EGR rate is increased. 10 % cold EGR shows higher efficiency when the engine is running at partial loads. But when it comes to 15 % EGR, hot EGR has the higher efficiency at higher loads due to the fact that when inlet temperatures are high, IC engines will have the higher efficiency.

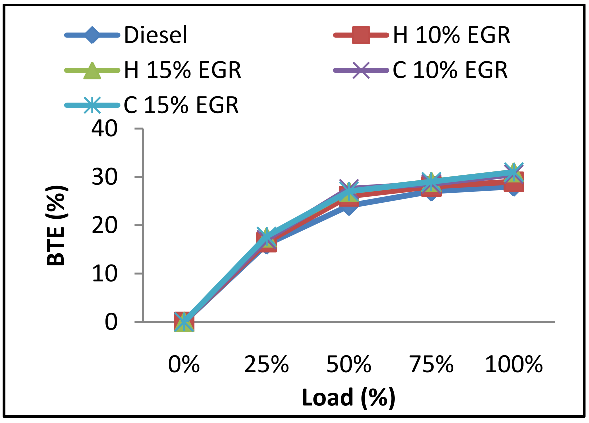

Figure 3: LOAD (%) Vs BTE (%) [3]

The other reason for this is that higher intake charge temperature increases the combustion velocity which leads to decrease in lead time thereby increasing the brake thermal efficiency. But the increase in brake thermal efficiency is marginal. Higher EGR rates would reduce the brake thermal efficiency.

Brake specific fuel consumption decreases as the load increases. As the EGR rate is increased the brake specific fuel consumption gets reduced and diesel without EGR has the higher specific fuel consumption.

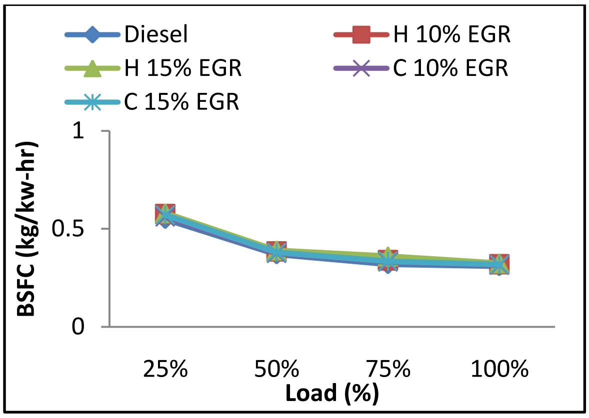

Figure 4: LOAD (%) Vs BSFC (kg/kw-hr) [3]

Vipul Jain, Dipesh Singh Parihar, Vaibhav Jain and Irfan H Mulla [4] the aim of this work is to review the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NOX emissions and observed without EGR system, when Brake power of the engine increases, the fuel consumption of the engine is also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and fuel consumption varies from 0.6945 kg/hr to 0.984 kg/hr and brake thermal efficiency varies from 14.85 % to 20.96 %.respectively. With EGR system, when Brake power of the engine increases, fuel consumption of the engine also increases and Brake thermal efficiency of the engine also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and fuel consumption varies from 0.7288 kg/hr to 1.1808 kg/hr and Brake thermal efficiency varies from 14.15% to 17.47%. From the above it is clear that the value of Fuel Consumption of the diesel engine with EGR is more than that of without EGR system at same brake power and the value of Fuel Consumption of the diesel engine with EGR increases than that of without EGR system at same brake power.

N. Ravi Kumar, Y. M. C. Sekhar, and S. Adinarayana [5] experimentally investigated Effects of Compression Ratio and EGR on Performance, Combustion and Emissions of Di Injection Diesel Engine and It is observed that irrespective of the compression ratio the volumetric efficiency of the engine is almost constant but the mechanical efficiency decreases between compression ratios 15 and 16 due to more friction power. At CR 19 the brake thermal efficiency reached maximum value of 17%. The brake thermal efficiency of the engine is low at CR 16 and later it slightly increases Overall with increase in compression ratio the specific fuel consumption decreases irrespective of the load except at compression ratio 16 due to less ignition delay and more combustion duration. It was found that with increase in compression ratio the brake thermal efficiency increases and specific fuel consumption decreases. It was observed that with raise in % of EGR the percentage increase in brake thermal was up to 13.5%. would reduce the brake thermal efficiency.

V. Manieniyan, S. Sivaprakasam[6] have been presented in graphical form in figure 5 and figure 6 respectively. From the graphs, it is observed that Brake thermal efficiency of 20% EGR was maximum for different loads (except at full load). This is probably due to increased combustion velocity because of higher intake charge temperature with EGR. With dissociation of carbon monoxide, free radicals were formed. This can also be a cause for improvement in efficiency. In full load 20% EGR, brake thermal efficiency was reduced by 1.5% in diesel. More exhaust gases produced due to predominant dilution effect of EGR in combustion chamber results in efficiency drop.

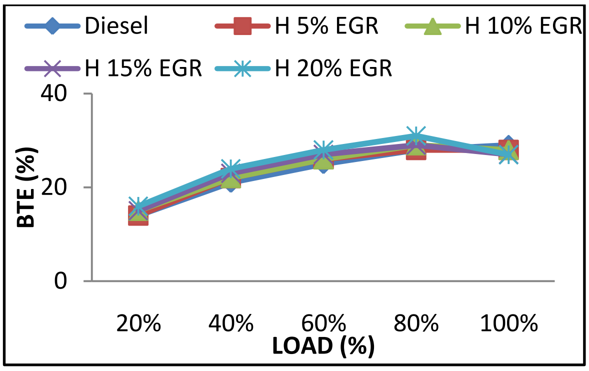

Figure 5: LOAD (%) Vs BTE (%) [6]

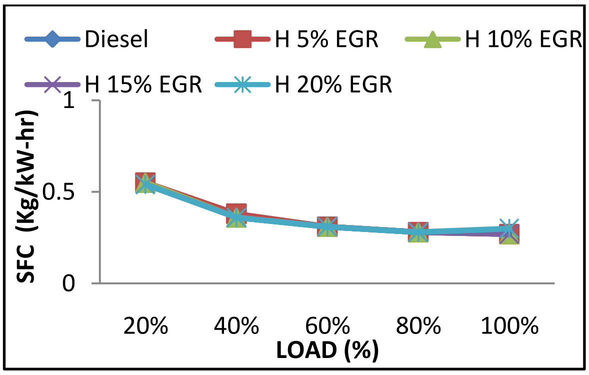

Figure 6: LOAD (%) Vs SFC (kg/kw-hr) [6]

Specific fuel consumption without EGR, under full load was found to be 0.2779 kg/kW-hr for diesel. Full load values of diesel with 5%, 10%, 15%, and 20% EGR were 0.2853, 0.2796, 0.2832 and 0.3050 kg/kW-hr respectively.

For higher level of EGR 20%, specific fuel consumption increased for diesel. Specific fuel consumption was lower in 20% EGR with diesel compare without EGR.

A. Mohebbi, S. Jafarmadar And J. Pashae [7] reported that Use of EGR has negative effect on BSFC, brake thermal efficiency and engine power but this negative effect is less when cooled EGR is used. The EGR temperature has no significant effect on exhaust gas temperature.

B. Effect on Exhaust Gas Temperature

P. Sai Chaitanya et al.[3] conducted an experiment to investigate the impact of hot and cold exhaust gas recirculation on diesel engine with cetane improver and observed that the variation of the exhaust gas temperature (EGT) along the different loads is presented in graph by taking load on X axis and EGT on Y axis as shown in figure 7.

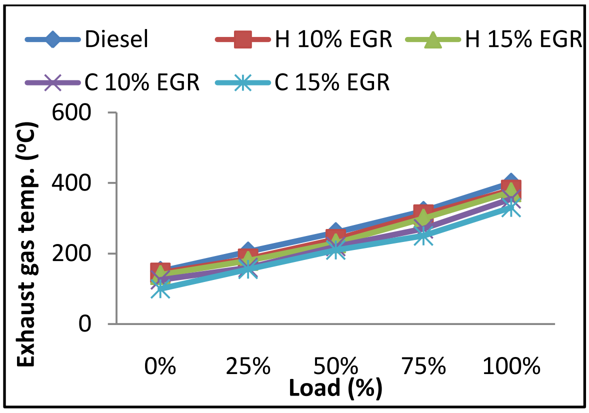

Figure 7 : LOAD (%) Vs Exhaust gas temp. (°C) [3]

It is clear that important reason for formation of NOx in the combustion chamber is extremely high temperature. The above graph indicates that as we increase the EGR rate the exhaust gas temperature reduces. So it can be concluded that the combustion chamber temperature also reduces and thus the formation of NOx also reduces. The cold EGR has a significant effect on the exhaust gas temperature.

Vipul Jain, Dipesh Singh Parihar, Vaibhav Jain and Irfan H Mulla [4] the aim of this work is to review the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NOx emissions and observed the variation of Exhaust Gas Temperature of the engine without EGR system at various Brake Power when Brake power of the engine increases, Exhaust Gas Temperature of the engine also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and respectively Exhaust Gas Temperature varies from 110 °C to 135 °C. With EGR, when Brake power of the engine increases, Exhaust Gas Temperature of the engine also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and Exhaust Gas Temperature varies from 105 °C to 129 °C. From the above it is clear that the value of Exhaust Gas Temperature of the diesel engine with EGR is less than that of without EGR system at same brake power.

V. Manieniyan, S. Sivaprakasam[6] have been presented in graphical form in figure 8. From the graphs, it is observed with increase in load, exhaust gas temperature also increases. As the hot EGR % increases the temperature also increases.

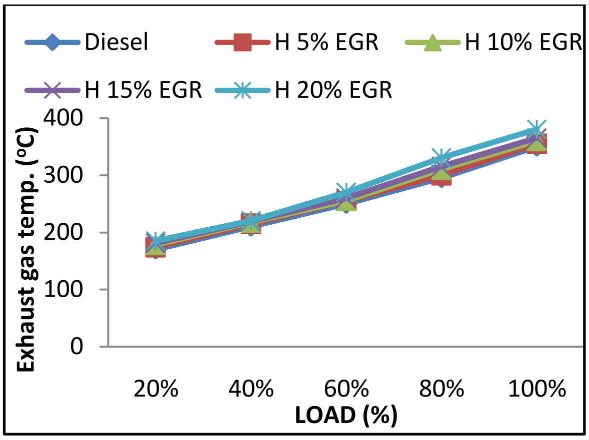

Figure 8 : LOAD (%) Vs Exhaust gas temp. (°C) [6]

V. EFFECT OF EGR ON EMISSIONS

Exhaust emissions like HC, CO, CO2, NOx, smoke opacity which have been evaluated by different researchers are reported in this section.

A. Effect on Smoke emission

P. Sai Chaitanya et al.[3] conducted an experiment to investigate the Impact of Hot and Cold Exhaust gas recirculation on Diesel Engine with Cetane Improver and observed that the smoke increases slightly as the EGR rates increases as shown in figure 9. This is because of the recirculation of exhaust gases into the cylinder. The effect of cold and hot EGR is insignificant in case of smoke opacity.

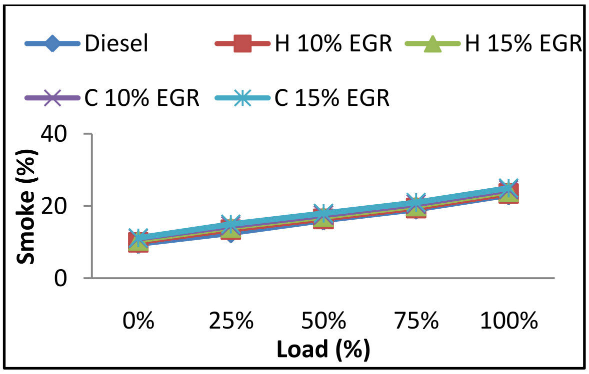

Figure 9 : LOAD (%) Vs Smoke (%) [3]

N. Ravi Kumar, Y. M. C. Sekhar, and S. Adinarayana[5] experimentally investigated Effects of Compression Ratio and EGR on Performance, Combustion and Emissions of Di Injection Diesel Engine and It is observed that The smoke opacity is gradually decreases at all compression ratios. The decrease in percentage varies from 17% to 4% from no load to full load.

V. Manieniyan, S. Sivaprakasam[6] As EGR level increases, smoke density also increases as shown in figure 10. In full load condition smoke density was 95.4 HSU for diesel at 20% EGR level.

EGR reduces availability of oxygen for combustion of fuel which results is relatively incomplete combustion and increased formation of particulate matter. This results in higher smoke level in case of EGR.

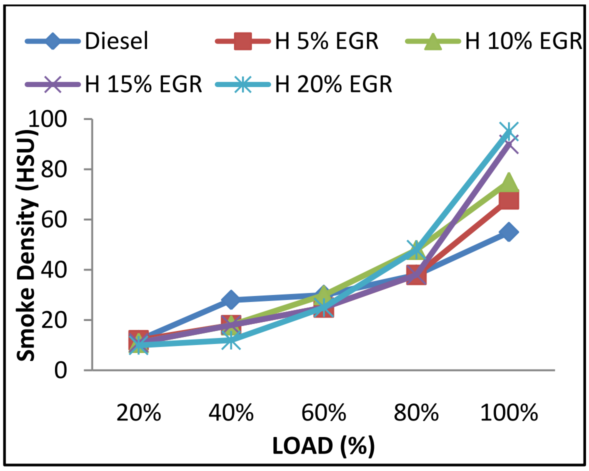

Figure 10 : LOAD (%) Vs Smoke Density (HSU) [6]

When EGR was used smoke level increased. EGR reduces availability of oxygen for combustion of fuel, which results in higher smoke level.

B. Effect on CO emission

Shaik Khader Basha et al [1] CO emissions with EGR were increased in part loads and decreases with higher loads as compared without EGR.

P. SaiChaitanya et al.[3] conducted an experiment to investigate the impact of hot and cold exhaust gas recirculation on diesel engine with cetane improver and observed that the increase of CO emissions as the load increases as shown in figure 11.

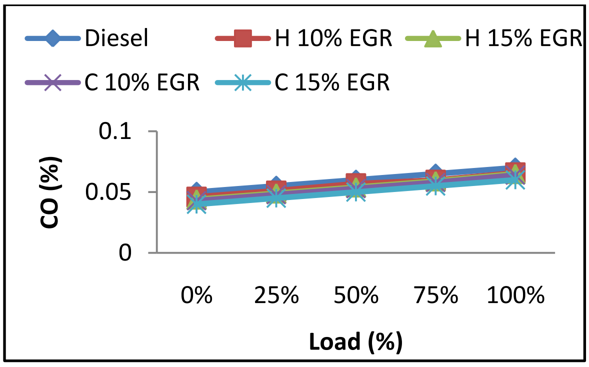

Figure 11: LOAD (%) Vs CO (%) [3]

As the EGR rate is increased CO emissions also gets reduced. This can be attributed to the reduction of available oxygen to combine with carbon.

Vipul Jain, Dipesh Singh Parihar, Vaibhav Jain and Irfan H Mulla [4] the aim of this work is to review the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NOx emissions and observed the variation of Carbon Monoxide (CO) of the engine without EGR system at various Brake Power when brake power increases emission of CO from Engine also increases.

Brake power of the engine varies from 1.232 kW to 2.464 kW and Carbon Monoxide (CO) varies from 0.04 % to 0.05 %.

With EGR system, when Brake power of the engine increases, Emission of Carbon Monoxide (CO) of the engine also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and Emission of Carbon Monoxide (CO) varies from 0.03 % to 0.04 %. From the above it is clear that the value of Emission of CO of the diesel engine with EGR is less than that of without EGR system at same brake power.

V.Manie niyan,S.Sivaprakasam[6] conducted an experiment to Analysis the effect of Exhaust Gas Recirculation on DI Diesel Engine Operating with Biodiesel and observed that In EGR CO emission increases due to oxygen deficient operation but still at low level compared to diesel operation without EGR.

C. Effect on NOx emission

Based on their experimental work, Shaik Khader Basha et al [1] have been presented in graphical form in figure 12 and figure 13 respectively. From the graphs, it is observed that NOx emission from hot EGR is comparatively higher than without EGR. Cold EGR of higher rates shows much effective in reducing NOx emission. 20%EGR

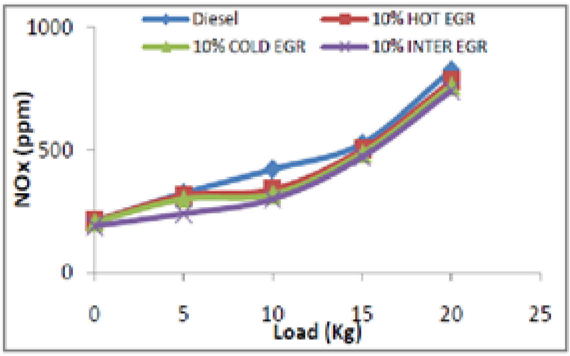

Figure 12: LOAD Vs NOx for 10% EGR [1]

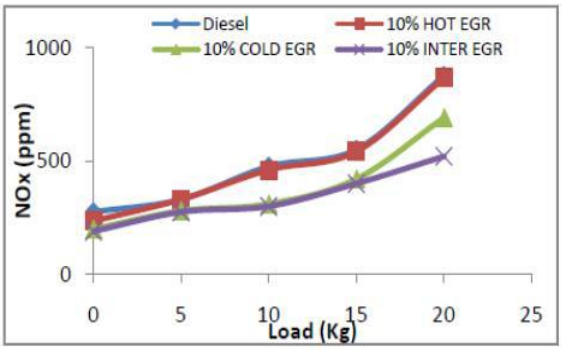

Figure 13: LOAD Vs NO_x (ppm) for 20% EGR [1]

P. Sai Chaitanya et al.[3] conducted an experiment to investigate the Impact of Hot and Cold Exhaust Gas Recirculation on Diesel Engine with Cetane Improver and observed that the significant effect of EGR can be found in NOx emissions as shown in figure 14.

The reason for reduction in NOx with EGR is the reduction of combustion temperature as a result of the addition of exhaust gases to the intake air which reduces the combustion temperature. Still higher EGR rates are able to reduce NOx emissions by a large amount, which however is accompanied by a reduction in BTE. There NOx reduces about 28% when engine run at full load.

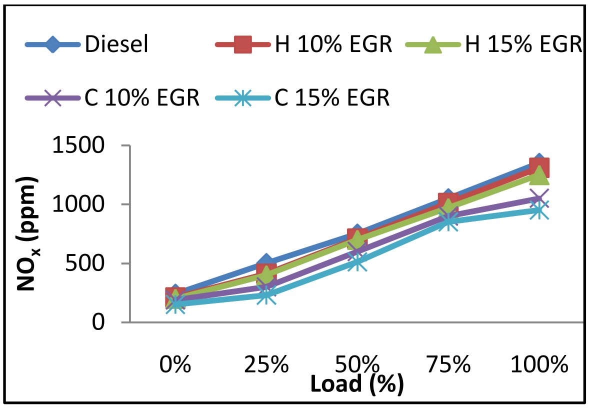

Figure 14: LOAD (%) Vs NO_x (ppm) [3]

Vipul Jain, Dipesh Singh Parihar, Vaibhav Jain and Irfan H Mulla [4] the aim of this work is to review the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NOX emissions and observed that the variation of Nitrogen Oxide (NOx) of the engine without EGR system, when Brake power of the engine increases, emission of nitrogen oxide (NOx) of the engine also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and emission of nitrogen oxide (NOx) varies from 759 ppm to 782 ppm. With EGR system, when Brake power of the engine increases, Emission of Nitrogen Oxide (NOx) of the engine also increases. The brake power of the engine varies from 1.232 kW to 2.464 kW and emission of nitrogen oxide (NOx) varies from 731 ppm to 764 ppm. From the above it is clear that the value of Emission of NOx of the diesel engine with EGR is less than that of without EGR system at same brake power.

N. Ravi Kumar, Y. M. C. Sekhar, and S. Adinarayana[5] experimentally investigated Effects of Compression Ratio and EGR on Performance, Combustion and Emissions of Di Injection Diesel Engine and It is observed that from the figure that with increase in percentage of EGR the NOx emissions are reduced. These are mainly due to low peak temperatures and complete combustion of re circulated gases in the cylinder. At compression ratio 15 and 10% EGR the percentage reduction of NOx was 26.5% and at full load it was 62.5%. It was found that with raise in % EGR the NOx emissions was gradually decreases by 11% to 85% at different compression ratios due to less flame temperatures and low oxygen content in the combustion chamber.

V.Manieniyan,S.Sivaprakasam[6] conducted an experiment to analysis the effect of Exhaust Gas Recirculation on DI Diesel Engine Operating with Biodiesel and observed that NOx value was found to be 736 ppm for diesel without EGR at full load condition.

This was due to peak combustion temperature inside the cylinder. With increases in EGR level, the NOx value gets reduced. With 20% EGR, NOx levels were 157 ppm for diesel. With increase in EGR level NOx level was reduced as shown in figure 15. Also reduction in brake thermal efficiency and large increase in smoke density were observed. In all load 20% EGR level NOx was reduced in diesel. With increases in EGR level, the NOx value gets reduced.

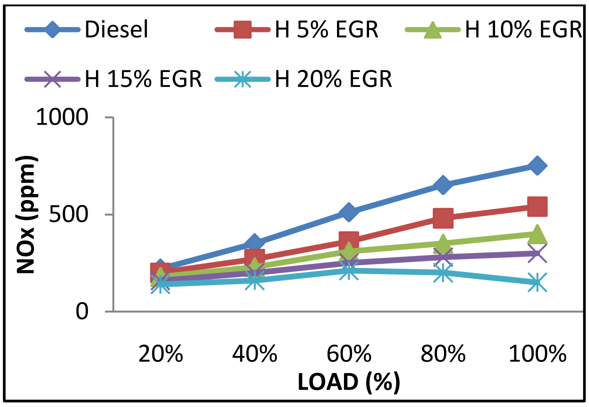

Figure 15: LOAD (%) Vs NO_x (ppm) [6]

A. Mohebbi, S. Jafarmadar And J. Pashae [7] reported that the cooled EGR is more effective than the hot EGR in terms of improving performance and reduction of engine emissions.

D. Effect on CO_2 emission

Based on their experimental work, Shaik Khader Basha et al [1] reported CO2 emission at 10% cold EGR percentages is very high than that of higher EGR rates as shown in figure 16.

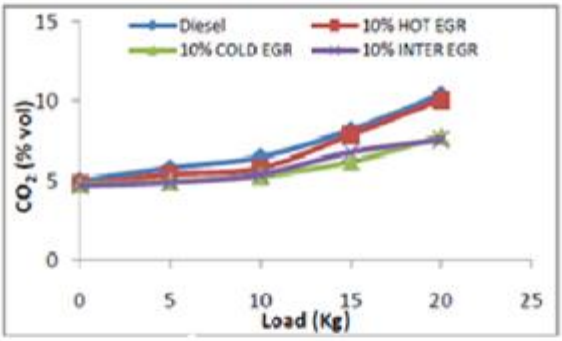

Figure 16 : LOADS Vs CO_2 for 10% EGR[1]

Vipul Jain, Dipesh Singh Parihar, Vaibhav Jain and Irfan H Mulla [4] the aim of his work is to review the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NO_X emissions and observed the variation of Carbon Dioxide (CO_2) of the engine without EGR, when Brake power of the engine increases, Emission of Carbon Dioxide (CO_2) of the engine is also increases.

The brake power of the engine varies from 1.232 kW to 2.464 kW and Carbon Dioxide (CO_2) varies from 1 % to 2 %. With EGR, when Brake power of the engine increases, Emission of Carbon Dioxide (CO_2) of the engine also increases. The brake power of the engine varies 1.232 kW to 2.464 kW and Emission of Carbon Dioxide (CO_2) varies from 0.8 % to 1 %. From the above it is clear that the value of Emission of CO2 of the diesel engine with EGR is less than that of without EGR system at same brake power.

V. Manieniyan, S. Sivaprakasam[6] have been presented in graphical form in figure 17. From the graphs, it is observed that the variation in CO levels for diesel operation with various EGR levels for different load conditions.

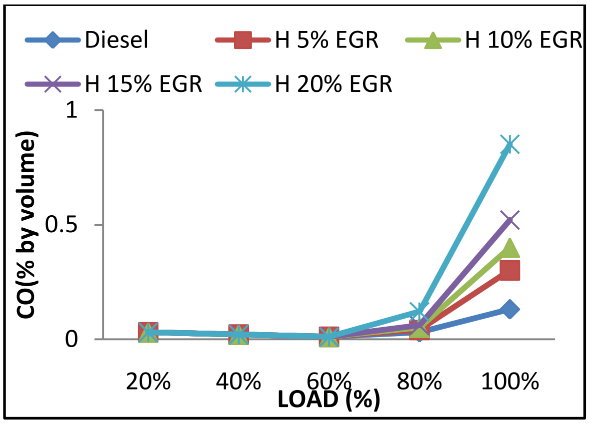

Figure 17: LOAD (%) Vs CO (% by volume) [6]

CO level for diesel varies from 0.14 (% by volume) for diesel at full load without EGR. In lean mixture condition engine emits less amount of carbon monoxide. In the case of 20% level EGR CO emission was 0.84 (% by volume) for diesel at full load. This increase in CO emission with EGR might be due to oxygen deficient operation.

E. Effect on HC emission

Vipul Jain, Dipesh Singh Parihar, Vaibhav Jain and Irfan H Mulla [4] the aim of his work is to review the potential of exhaust gas recirculation (EGR) to reduce the exhaust emissions, particularly NOX emissions and observed the variation of Hydro Carbon (HC) of the engine without EGR system, when Brake power of the engine increases, Emission of Hydro Carbon (HC) of the engine decreases. The brake power of the engine varies from 1.232 kW to 2.464 kW and Emission of Hydro Carbon (HC) varies from 18.5 ppm to 16.4 ppm. With EGR system, when Brake power of the engine increases, the Emission of Hydro Carbon (HC) of the engine decreases. The brake power of the engine varies from 1.232 kW to 2.464 kW and Emission of Hydro Carbon (HC) varies from19.5 ppm to 17 ppm.

From the above it is clear that the value of Emission of HC of the diesel engine with EGR is more than that of without EGR system at same brake power.

V.Manieniyan,S.Sivaprakasam[6] have been presented in graphical form in figure 18. From the graphs, it is observed that In Full load condition HC emission was measured as 35 ppm in diesel without EGR. At the same full load condition with higher EGR level HC emission varies from 35 to 66 ppm in diesel. This is due to richer mixture at full load and oxygen deficiency might have dominated as EGR was applied.

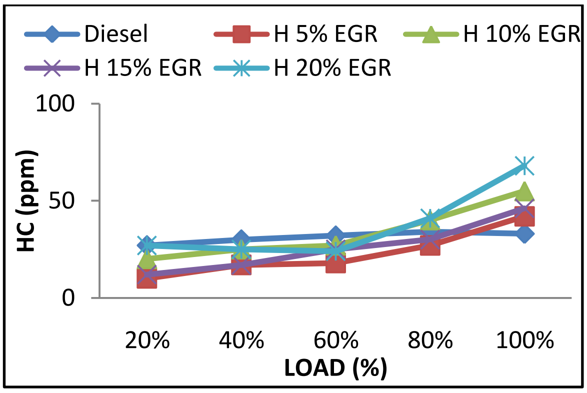

Figure 18: LOAD (%) Vs HC (ppm) [6]

CONCLUSION:

Experimental results shows 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 the combustion temperature which leads to increase in formation of NOx. By increasing the cooled EGR rates reduces the emissions more significantly.

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