Comparative Study on effect of Exhaust Gas Recirculation (EGR) on Performance and Emission characteristics of a Diesel Engine

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Abstract - **Diesel engine emissions are a major threat agent to the environment and human health, both in terms of global warming and carcinogenic action of these elements. This is especially critical concerning nitrogen oxides (NOx), Hydrocarbons (HC), Carbon monoxide (CO) and particulate matter (PM).With the advent of stringent emissions regulations, the Exhaust Gas Recirculation (EGR) has become a critical component in diesel engine systems to reduce NOx (nitrogen oxides) emissions. This is accomplished by returning cooled exhaust gas back to the engine. The EGR is designed to cool this re-circulated exhaust gas with coolant, thereby reducing its volume and increasing its density. In this paper, The impact of EGR on Diesel operations and Emission characteristics are analyzed. EGR can be applied to diesel engine without sacrificing its efficiency and fuel economy and NOx reduction can thus be achieved. The increase in CO, HC, and PM emissions can be reduced by using exhaust after-treatment techniques, such as diesel oxidation catalysts (DOCs) and soot traps.**

keywords - **Diesel Engine, Exhaust gas recirculation system (EGR), Air-Fuel ratio (AFR), Oxides of Nitrogen (NOx)**

I. INTRODUCTION

Today, diesel engines are the backbone of the commercial transport industry used in trucks, ships, buses, etc. to transport goods from one place to another as Diesel engines have high thermal efficiencies, due to their high compression ratio and fuel lean operation. The high compression ratio of the diesel engine produces the high temperatures in the combustion chamber. Diesel Engine exhaust primarily consist of four main pollutants which are Unburned hydrocarbons (HC), Carbon monoxide (CO), Particulate matter (PM) and oxides of Nitrogen (NOx). Diesel engine combustion generates large amounts of Oxides of nitrogen (NOx) because of the high flame temperature in the presence of abundant oxygen and nitrogen. Oxides of nitrogen (NOx) is produced in very small quantities can cause pollution. An oxide of nitrogen is dangerous for human health and environment. Strict emission standards are now in place that set specific limits to the amount of pollutants that can be released into the environment. Therefore, there is an urgent need for diesel engine makers to come up with technologies that can efficiently combat these exhaust emissions emission without compromising with engine performance.

1. Pollutants of Diesel Engine

Diesel Engine exhaust primarily consist of four main pollutants which are Unburned hydrocarbons (HC), Carbon monoxide (CO), Particulate matter (PM) and oxides of Nitrogen (NO_x).

The formation of the pollutants largely depends on the Air-Fuel ratio (AFR) of the engine. AFR is the ratio of air consumed by the engine compared to the amount of fuel. When the amount of air and fuel in enough to produce a chemically complete combustion reaction then the ratio is called stoichiometric AFR. For diesel engines stoichiometric AFR has 14.5 parts of air for each part of fuel (14.5:1). An engine can either have a lean or a rich combustion. If AFR number is less than the stoichiometric AFR (<14.5:1), it means less air during combustion and engine runs in rich condition. Contrarily, if an AFR number is higher than the stoichiometric AFR (>14.5:1), it means more air and the engine runs in lean condition. Lean combustion is characteristic of a diesel engine.

1.1 Carbon Monoxide (CO)

Carbon monoxide formation largely depends on the Air-fuel ratio (AFR). If the engine runs on rich condition (i.e. less air) during the combustion, then due to the deficiency of air in the combustion chamber incomplete oxidation occurs and a large proportion of carbon is unable to get converted into CO_2. Diesel engines are lean combustion engine so CO is produced in very small proportions.

Carbon monoxide is an odourless and colourless gas which when inhaled binds with hemoglobin and reduces its capacity to transfer oxygen. It can affect function of different organs and can result in confusion, light-headedness, headache and impaired concentration. In the worst case Carbon monoxide poisoning can even lead to death.

1.2 Hydrocarbons (HC)

Hydrocarbons results due to the incomplete combustion of the hydrocarbon fuel. Air-fuel mixture temperature near the wall in combustion chamber is significantly less than the centre of the cylinder. Because of this flame quenching occurs at the walls of the cylinder and a small proportion of fuel remain unburned. This leads to the formation of hydrocarbons. Hydrocarbons in diesel exhaust contains a lots of species, such as alkanes, alkenes and aromatics. Some of these species are inert while others are highly reactive and contributes in the smog formation. Diesel combustion normally produce low levels of hydrocarbon. Hydrocarbons can be harmful and cause environmental and health problems. They are toxic and can cause respiratory tract irritation and can even cause cancer. They can produce smog and cause acid rain.

1.3 Oxides of nitrogen (NOx)

Oxides of nitrogen, NO and NO_2 are collectively referred as NO_x. In a diesel exhaust NO constitutes of about 85 – 90% of NO_x. After its emission, NO reacts with atmospheric air to form NO_2. NO is a colourless and odourless gas while NO_2 has reddish brown colour with pungent smell.
The amount of NO_x produced during combustion largely depends on the maximum temperature in the cylinder, concentrations of the oxygen and the residence time. Highly compressed hot air is used in diesel combustion to ignite the fuel. This atmospheric air contains Nitrogen and Oxygen. Normally Nitrogen does not take part in the combustion process and remains unreacted throughout the combustion process. However, if in cylinder temperatures reaches to around 1600°C, it causes nitrogen to react with oxygen and generate NO_x emissions. Most of the NO_x is produced early in the combustion process when the flame temperature is the maximum. Therefore NO_x emission increases with the increase in temperature in the combustion chamber.Among all the vehicles types diesel vehicles are the main contributors to NO_x emissions. 85% of all the NO_x emissions from all the mobile sources comes from diesel operated vehicles.
Nitrogen oxide emissions are responsible for several environmental and health problems. These emissions are the cause of acidification, formation of ozone, smog formation, acid rains etc. NO_2 is more toxic than NO and causes several lung diseases.

1.4 Particulate Matter (PM)

Particulate matter is an intricate mixture of very small particles and liquid droplets that get suspended in the air. Particulate matter is produced in the combustion chamber because of the incomplete combustion of fuel and lubrication oil. The formation of particulate matter largely depends on factors such as fuel quality, combustion temperature, lubrication oil quality and consumption, exhaust has cooling, etc. Diesel PM Emission consist of three key components: soot, soluble organic fraction (SOF), and inorganic fraction (IF). Soot (Black smoke) accounts for more than 50% of the total PM emission. SOF are the heavy hydrocarbons absorbed or condensed on the soot. SOF is derived partly from lubricating oil and partly from unburned fuel.
PM emission can have adverse effects on environment and human health. Inhaling of these particles can cause asthma, premature death, lung cancer and many other fatal diseases. These emission pollute environment and contribute to global climate change.

2. Mechanism of Oxides of nitrogen (NO_X) formation and its control

Nitrogen Oxides which occurs only in the engine exhaust are a combination of nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrogen and oxygen react at relatively high temperature. NOx is formed inside the combustion chamber in post-flame combustion process in the high temperature region. The main regions for the formation of NOx are the high peak combustion temperature and availability of oxygen. In the presence of oxygen inside the combustion chamber at high combustion temperatures, the following chemical reactions will takes place.

$$N_2 + O_2 = 2NO$$

$$N_2 + 2H_2O = 2NO + H_2$$

A significant amount of NO will be formed at the end of combustion. The majority of NO formed will however decompose at the low temperatures of exhaust. But, due to very low reaction rate at the exhaust temperature, a part of NO formed remains in exhaust. The NO formation will be less in rich mixtures than in lean mixtures.

2.1 NO_X Emission control:

NOx emission is closely related to temperature and oxygen content in the combustion chamber. Any process to reduce cylinder peak temperature and concentration of oxygen will reduce the oxides of nitrogen. This suggests a number of methods for reducing the level of nitrogen oxides. The following are the three methods for reducing peak cycle temperature and thereby reducing NOx emission.

- Water injection.
- Catalyst
- Exhaust gas recirculation (EGR)

2.1.1 Water injection

In the Diesel engines, NOx is generated during combustion. To reduce the level of nitrogen oxides (NOx) water injection method is used. NOx emission reduces with increase in water injection rate per kg of fuel. The specific fuel consumption decreases a few percent at medium water injection rate. The water injection system is used as a device for control the NOx emission from the engine exhaust.

2.1.2 Catalyst

In the presence of CO, By using the catalyst nitrogen oxide (NOx) emission reduced. In the IC engines catalytic converter is used to control the emission levels of various pollutants by changing the chemical characteristics of the exhaust gases. A catalytic convertor is shown in Figure1. In modern vehicles catalytic convertor is used to control the emissions.

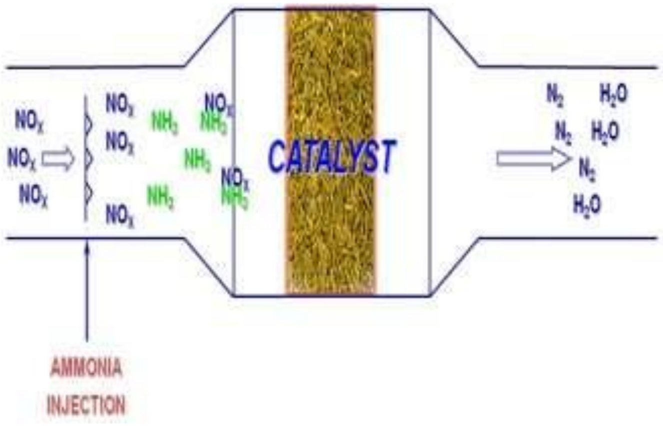


Figure 1. Catalyst

2.1.3 Exhaust Gas Recirculation (EGR):

Exhaust Gas Recirculation is method which is used for NOx control. The exhaust gases mainly consist of carbon dioxide, nitrogen etc. and the mixture has higher specific heat compared to atmospheric air. Carbon dioxide and water vapour present in engine exhaust gas, sore-circulated exhaust gas entering in the combustion chamber with fresh air. From air Displacement, small amount of oxygen is available in the intake mixture for combustion. Air fuel ratio is reduced due to availability of oxygen . So reduction in air–fuel ratio affects exhaust emissions. Re-circulated exhaust gas mixing with fresh intake air, so specific heat of intake mixture increases and from this flame temperature reduced. Thus combination of small oxygen quantity in the intake air and reduced flame temperature reduces rate of NOx formation reactions .The EGR (%) is defined as the mass percent of the re-circulated exhaust (MEGR) in the total intake mixture (Mt).

$$\text{EGR}(\%) = (\text{MEGR}/\text{Mt}) \times 100$$

From above three methods, Exhaust Gas Recirculation (EGR) is the most efficient and widely used system to control the formation of oxides of nitrogen inside the combustion chamber of Diesel engine in order to abide the legal standards on its emissions, And to optimize the engine performance and increase its efficiency. The exhaust gas for recirculation is taken through an orifice and passed through control valves for regulation of the quantity of recirculation.

3. Exhaust Gas Recirculation system

Exhaust Gas Recirculation system is one of the most effective way to reduce NO_x emission from the diesel exhaust as it reduces the combustion temperatures and oxygen concentrations inside the combustion chamber. [10]

An EGR system most commonly consist of the following components:

- EGR control valves, device which controls the amount of exhaust gases directed back into the combustion chamber
- EGR coolers, heat exchanger devices that used coolant to reduce the exhaust gas temperatures before directing them back into the combustion chamber
- Piping [9]

Figure 2 depicts layout of a high pressure loop, cooled EGR system which has been used in AUDI 3.3 L V8 TDI engine. In an EGR system a portion of spent exhaust gas is redirected into the combustion chamber. The gas passes through EGR control valve and then proceeds to the EGR cooler. It is imperative to cool down the exhaust gases prior to recirculation to prevent temperature rise in the combustion chamber. Subsequently, the cooled exhaust gases passes through the EGR Intake throttle where they get mixed with the high pressure, cooled (to improve density) combustion air. The mixture of air and exhaust gases is then inducted into the combustion chamber through and intake manifold. [9]

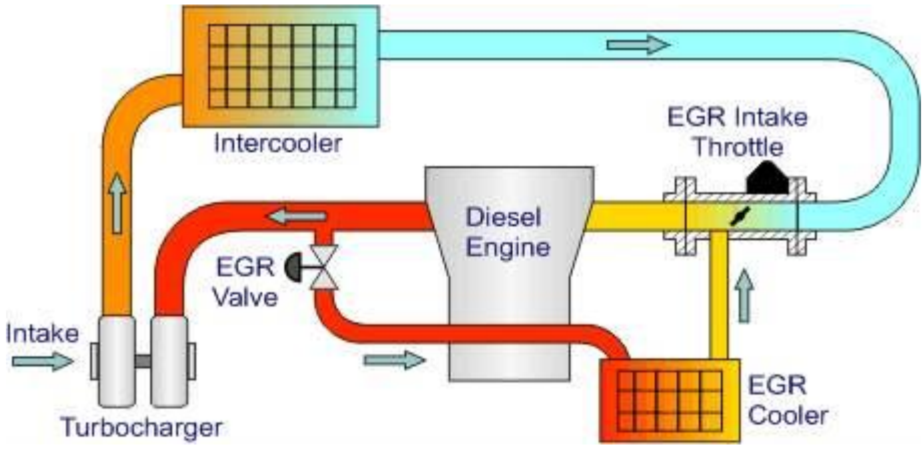


Figure 2. Exhaust Gas Recirculation System [9]

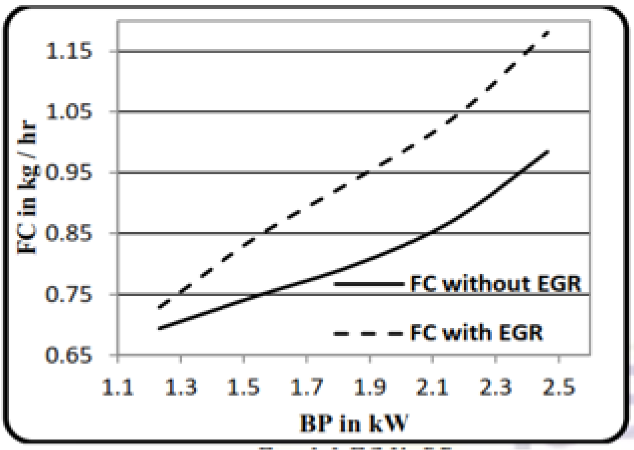
The exhaust gases which are directed back into the combustion chamber mainly contains carbon dioxide, water vapour and nitrogen. These gases have higher specific heat capacity than atmospheric air. Oxygen deficient recirculated gases displaces the fresh air entering the combustion chamber and reduces the oxygen content available for combustion. This in turn lowers the effective Air fuel Ratio (AFR) and affects the exhaust emissions significantly. The exhaust gas-atmospheric air mixture increases the specific heat of the intake mixture and results in the significant reduction of flame temperature. Therefore, lower oxygen content in the intake mixture and reduced flame temperatures together results in the reduced NO_x formation rates. [10]
The effects of exhaust gas addition to the intake air in a diesel combustion can be summarized below:

- Heat capacity of the intake charge increases which results in lower flame temperatures
- The intake charge is diluted by exhaust gas and makes it oxygen deficient
- The exhaust gas addition leads to an increase in inlet temperatures
- EGR addition causes changes in the flame structure which alters combustion duration or increases the ignition delay time
- Due to the recirculation Inlet concentration of pollutants increases. [11]

II. Literature Review

A number of studies have been published regarding the effects of Exhaust Gas Recirculation (EGR) system on the performance and emission characteristics of diesel engines. Several of these have been considered and are reviewed here to highlight the developments in this area of study.

Vipul Jain et.al [1] investigated suitability of Exhaust Gas Recirculation system for use in a C.I. engine and evaluated the



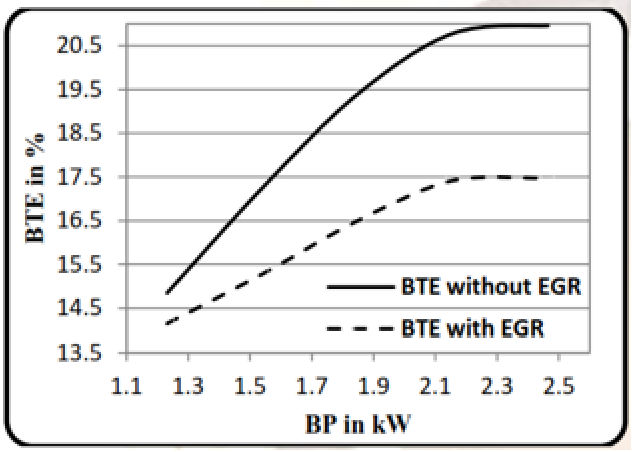


Figure 3. Fuel Consumption vs. Brake Power **Figure 4. Brake Thermal Efficiency vs. Brake Power**

performance and emission characteristics of the engine. They found that The engine performance on EGR system, Exhaust Gas Temperature reduces as compared to that of without EGR system, so it is beneficial for surrounding. They compared C.I. engine with and without EGR system of variation in Fuel Consumption with respect to Brake Power. From the Figure 3, it was clear that the value of Fuel Consumption of the diesel engine with EGR increases than that of without EGR system at same brake power. The Brake Thermal Efficiency (BTE) of the engine was partially lower as shown in Fig 4. The Brake Specific Fuel Consumption (BSFC) of the engine was partially higher when EGR system was implemented with engine. They also investigated emission characteristics of Diesel engine. Emission of Oxide of Nitrogen (NO) was very much reduced by implementation of EGR system.

Emission of Carbon Dioxide (CO_2) and Carbon Mono-oxide (CO) was also reduced. Emission of Hydro Carbon (HC) was increased by implementing EGR system with engine than that of operating engine without EGR system.

Avinash Kumar Agrawal et. al [2] investigated performance of A two-cylinder constant speed diesel engine generator set. The result was found that a decrease in the exhaust temperatures with increasing EGR as shown in Fig. 5, therefore it was concluded that the combustion chamber temperatures also decreased and thus the formation of NOx was decreased. This reduction in exhaust gas temperature did not affect the thermal efficiency. It was concluded that thermal efficiency remains unaffected by EGR. However, at high loads and at EGR rates above 15%, thermal efficiency was decreased slightly. This may be due to the fact that the amount of fresh oxygen available for combustion gets decreased due to replacement by exhaust gas. However particulate matter emission in the exhaust increased, as evident from smoke opacity observations as shown in Fig. 6.

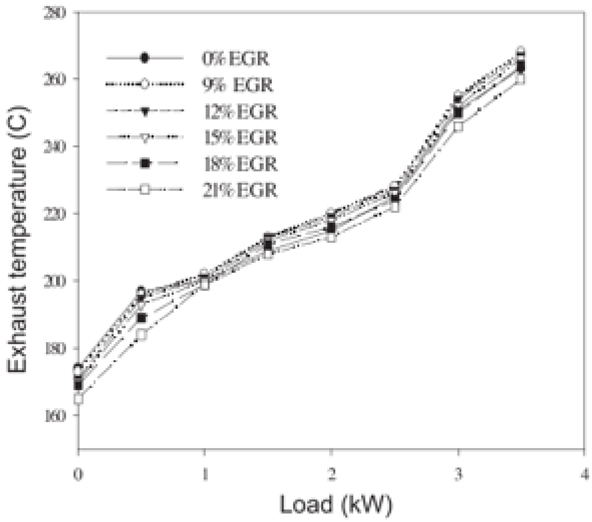


Figure 5. Effect of exhaust gas temperature vs load

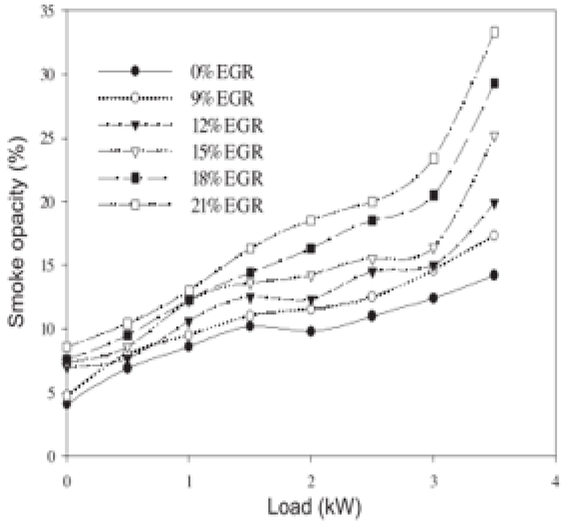


Figure 6. smoke opacity in exhaust gas vs. load

Rishant Sharama et.al [3] were conducted experiment on vertical single cylinder, water-cooled engine using two compression ratios 7 and 8. Data was collected with and without EGR so as to see how EGR affects the engine performance and its emissions. The EGR was found to decrease the value of NOx and HC Emissions by an appreciable amount. EGR was found to be more effective at higher values of compression ratios. EGR was also found to be effective in reducing knock as it reduces the Heat Release Rate as well as Cylinder Pressure. Figure 8 showed the Heat Release Rate Variation with Crank Angle.

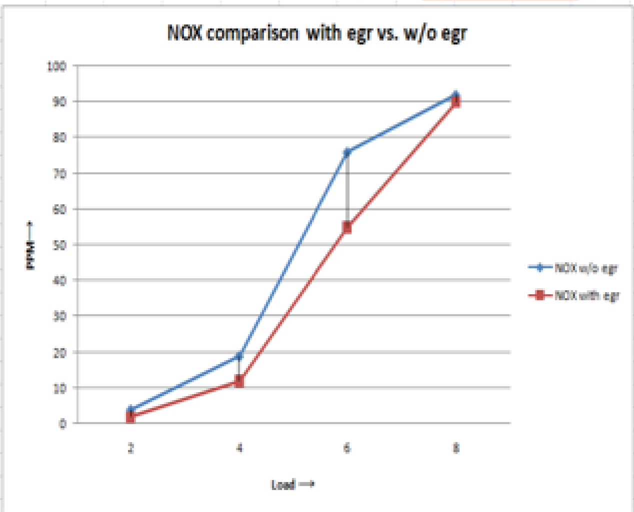


Figure 7. NOX Emissions Variation With and W/O EGR At Various Loads At CR 8

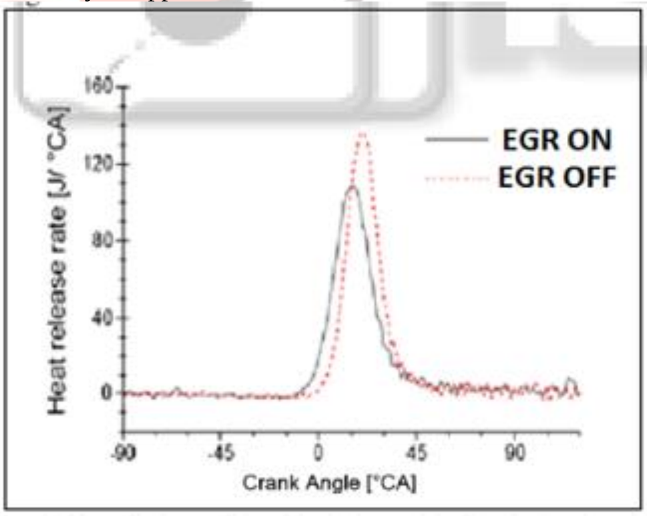


Figure 8.Heat Release Rate Variation with Crank Angle with EGR ON And OFF

Jitender Singh et. al [4] investigated EGR system used with turbocharged engine in modern vehicles. The following major findings from using the EGR system with turbocharged engine were found following result.

- The thermal efficiency was increased of the engine when EGR system was used in the modern vehicles.
- Improvements in the fuel economy and also control the emissions using EGR system.
- Using the EGR system with turbocharged engine, NOx production reduced in the cylinder of the engine.

Jaffar Hussain et.al [5] studied the effect of EGR on the performance and emissions, carbon deposits on a three-cylinder constant speed direct injection diesel engine generator set. They found that Thermal efficiency was slightly increased and BSFC was decreased at lower loads with EGR compared to without EGR. But at higher loads, thermal efficiency and BSFC are almost similar with EGR than without EGR. Exhaust gas temperature was decreased with EGR, but NOx emission decreased significantly. It can be observed that 15% EGR rate was found to be effective to reduce NOx emission substantially without deteriorating engine performance in terms of thermal efficiency, BSFC, and emissions. At lower loads, EGR reduces NOx without deteriorating performance and emissions. At higher loads, increased rate of EGR reduces NOx to a great extent but deteriorates performance and emissions. Thus, it can be concluded that higher rate of EGR can be applied at lower loads.EGR can be applied to diesel engine without sacrificing its efficiency and fuel economy and NOx reduction can thus be achieved. The increase in CO, HC, and PM emissions can be reduced by using exhaust after-treatment techniques, such as diesel oxidation catalysts (DOCs) and soot traps.

Deepak Agarwal et al. [6,7] investigated the effect of EGR on soot deposits, and wear of vital engine parts, especially piston rings, apart from performance and emissions in a two cylinder, air cooled, constant speed direct injection diesel engine, which is typically used in agricultural farm machinery and decentralized captive power generation. Reductions in NOX and exhaust gas temperature were observed but emissions of particulate matter (PM), HC and CO were found to have increased with usage of EGR. The engine was operated for 96 hr in normal running conditions and the deposits on vital engine parts were assessed. The engine was again operated for 96 h with EGR and similar observations were recorded.

P. V. Walke et.al [8] were conducted on computerized single cylinder 4-stroke kirloskar diesel engine with eddy current dynamometer to evaluate the performance of EGR system. They found that Brake thermal efficiency decreased with increasing EGR rates. However, this decrease is marginal. Brake specific fuel consumption increased marginally with increasing exhaust Gas Recirculation rates at high load. Figure 9 depicted that the smoke emission increased with the increase in EGR rates for different torque. This significant increase in smoke is due to Exhaust Gas Re-circulation reduce the overall air/fuel ratio which enhances the increase in particulates. Re-circulated exhaust gas contain particulates which further contribute in raising smoke level. The concentration of smoke density increases. Figure 10 showed that The exhaust gas recirculation (EGR) has definite impact on NOx reduction.

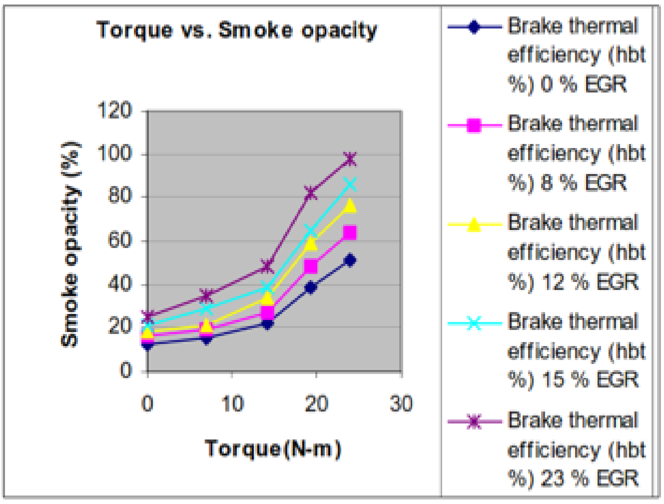


Figure 9. Torque vs. Smoke Opacity

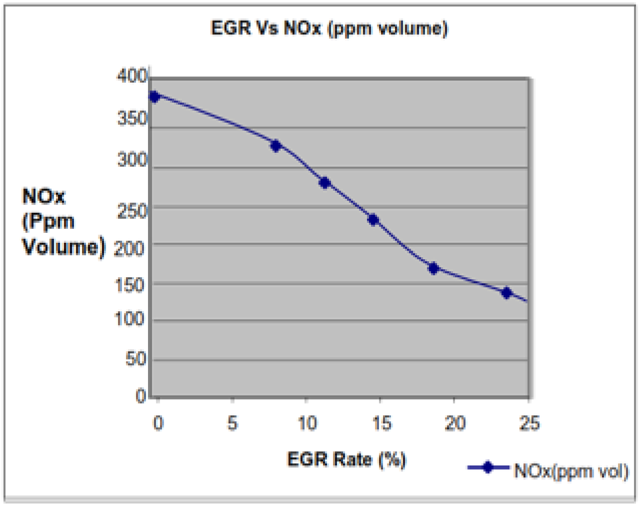


Figure 10. EGR Rate vs. NO

III. CONCLUSION

Exhaust Gas Recirculation (EGR) is the most efficient system to control the formation of oxides of nitrogen inside the combustion chamber of Diesel engine in order to abide the legal standards on its emissions, and to optimize the engine performance and increase its efficiency. The conclusions from the results of this review regarding effect of Exhaust Gas Recirculation (EGR) on Performance and Emission characteristics of a Diesel Engine can be summarized as follows:

- Thermal efficiency increases and BSFC decrease at lower loads with EGR compared to without EGR. But at higher loads, thermal efficiency tends to decrease slightly.
- The Brake Thermal Efficiency (BTE) of the engine partially decrease.
- EGR is more effective at higher values of compression ratios.
- EGR is also found to be effective in reducing knock as it reduces the Heat Release Rate as well as Cylinder Pressure.
- When EGR system is used in turbocharged diesel engine, the thermal efficiency of the engine increase, also there is improvements in the fuel economy and control the emissions.
- Exhaust Gas Temperature reduces as compared to that of without EGR system, so it is beneficial for surrounding.
- Emission of Oxide of Nitrogen (NO) is very much reduced by implementation of EGR system.
- Emission of Carbon Dioxide (CO_2) and Carbon Mono-oxide (CO) reduces.

- Emission of Hydro Carbon (HC) increases by implementing EGR system with engine than that of operating engine without EGR system.
- Particulate matter emission in the exhaust increases.
- The increase in CO, HC, and PM emissions can be reduced by using exhaust after-treatment techniques, such as diesel oxidation catalysts (DOCs) and soot traps.
- At lower loads, EGR reduces NOx without deteriorating performance and emissions. At higher loads, increased rate of EGR reduces NOx to a great extent but deteriorates performance and emissions. Thus, it can be concluded that higher rate of EGR can be applied at lower loads.

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