EFFECTS OF EXHAUST GAS RECIRCULATION ON EMISSION AND PERFORMANCE OF DIESEL ENGINES
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Abstract
The Exhaust Gas Recirculation (EGR) system is designed to reduce the amount of oxides of nitrogen (NOx) created by the engine during operating periods that usually result in high combustion temperatures. NOx is formed in high concentrations whenever combustion temperatures exceed about 2000K. Exhaust gas recirculation is a very effective technique to reduce NOx emission in diesel engine because it increases the CO2 concentration in combustion chamber which increases the heat capacity of the intake charge, thus there is a reduction in the cylinder peak temperature. Because of the Lower cylinder peak temperature NOx formation reduces. However, particulate emission is comparatively in using EGR technique. With the increase in the recirculated amount of exhaust gas, particulate emission increases and engine loses power. With increasing EGR, soot content and PAN increases in the engine oil of combustion chamber. This increased amount of soot and PAN increases the wear and corrosion of the engine components. The aim of this paper is to study the effect of using EGR on emission and performance in diesel engine. High EGR flow is necessary during cruising and mid-range acceleration, when combustion temperatures are typically very high. Low EGR flow is needed during low speed and light load conditions.

Keywords- Exhaust Gas Recirculation (EGR), oxides, particulate emission.

I. Introduction
In diesel engines, NOx formation is the major issue. NOx formation is a temperature dependent phenomena and it generates when the combustion chamber temperature increases beyond 2000K. One very simple way to reduce this NOx emission is late injection of fuel in the combustion chamber, but it increases the fuel consumption. Exhaust Gas Recirculation (EGR) is more effective technique to reduce NOx emission. In fact, partial recirculation of exhaust gas, which is not a new technique, has recently become essential, in combination with other techniques, for attaining lower emission levels. There are many reasons for this interest. First reason is the proposals of the future European directive establishes, and even more stringent limits for NOx emissions. Second reason is the further reductions in NOx emissions have probably become the most difficult target to attain, which can create reverse effect on other recently used techniques, such as high supercharging, an improved mixing process by more efficient injection systems etc. Third reason is the development of a new generation of EGR valves and improvements in electronic controls allow a better EGR accuracy and shorter response time. Fourth reason is the most common operating conditions, mainly in passenger cars, has moved to lower engine loads, owing to the increase in urban traffic density, and it must be considered that it is mainly at partial loads where EGR is indicated because of its higher oxygen content. Modern engines implement EGR to reduce NOx. NOx is produced during the combustion event at high temperatures. Oxygen combines with nitrogen to form NO and NO2. NOx combines with hydrocarbons or volatile organic compounds in sunlight to form SMOG. Since the 1970s, automobiles have used EGR to control NOx production. EGR controls NOx by lowering the combustion temperature and reducing the oxygen content in the combustion chamber. Most EGR is used at cruising speeds with moderate acceleration. Other times EGR is turned off due to undesirable effects. EGR is effective up to about 15% before it starts causing misfires or other engine problems. Most EGR systems use a
vacuum solenoid to open and close a valve at the desired times to introduce exhaust gas into the intake system. EGR systems have helped to clean up the air quality of many cities around the world.

II. NOx Formation
In the early 1970s exhaust gas recirculation was introduced, in vehicles, as a means to control NOx. NOx stands for Oxides of Nitrogen or Nitrogen Oxide. The primary compounds found in NOx are NO and NO2. Nitric oxide (NO) is the predominant oxide of nitrogen produced inside the engine cylinder. The principal source of NO is the oxidation of atmospheric nitrogen. NOx is formed during the combustion due high temperature. It is generally accepted that in combustion of near stoichiometric fuel-air mixtures the principal reactions governing the formation of NO from molecular nitrogen are, [6]

\[
\begin{align*}
O + N_2 & \rightarrow NO + N \\
N + O_2 & \rightarrow NO + O \\
N + OH & \rightarrow NO + H
\end{align*}
\]

NO forms in both flame front and post flame gases. Although the amount of NO2 in total NOx emission is less but still it is around 30% for the diesel engines. The mechanism of NO2 formation is below, [6]

\[
NO + HO_2 \rightarrow NO_2 + OH
\]

Subsequently, conversion of NO2 to NO occurs,

\[
NO_2 + O \rightarrow NO + O_2
\]

NOx in itself is not a huge problem, but what it does in certain areas of the world is. When NOx accumulates in a sunny area in the presence of either Hydrocarbons (HCs) or Volatile Organic Compounds (VOCs), it produces what has been termed SMOG. These accumulations happen in valleys and areas where weather conditions do not easily disperse the NOx.

III. Implementation of EGR
The implementation of EGR is straightforward for naturally aspirated Diesel engines because the exhaust tailpipe backpressure is normally higher than the intake pressure. When a flow passage is devised between the exhaust and the intake manifolds and regulated with a throttling valve, fig 1, exhaust gas recirculation is established. The pressure differences generally are sufficient to drive the EGR flow of a desired amount, except during idling whilst a partial throttling in the tailpipe itself can be activated to produce the desired differential pressure. If the exhaust gas is recycled to the intake directly, the operation is called hot EGR. If an EGR cooler is applied to condition the recycled exhaust, it is called cooled EGR.

![Fig. 1 Exhaust gas recirculation [11]](image1)

In modern turbocharged diesel engines, implementation of EGR is more difficult. There are mainly two types of system used for turbocharged diesel engine: (i) Low pressure loop EGR (fig 2) (ii) High pressure loop EGR (fig 3). A low pressure loop EGR is less favorable than the high pressure loop EGR because of the larger volume contaminated with exhaust gas in dynamic operation.

![Fig. 2 Low pressure loop EGR [11]](image2)
IV. Effects of EGR on Emission and Performance

At present, EGR technique is one of the most effective techniques for reducing NOx emission in internal combustion engines. There are mainly three explanations of effect of EGR on NOx reduction. First, EGR causes the increase in ignition delay, which has the same effect as retarding in injection timing. Secondly, exhaust gases always contain CO₂, N₂ and moisture contents. As the heat capacity of EGR is much higher than the fresh air, it increases the heat capacity of the combustion mixture. Because of this increased heat capacity of the combustion mixture, the peak temperature reduces in the combustion chamber. Subsequently, the formation of NOx reduces because of the lower combustion temperature. Thirdly, the dilution theory, it reduces the combustion temperature because of the recirculated saturated gases such as CO₂, N₂ and moisture. EGR ratio is defined as

\[
\text{EGR}_{\text{ratio}} = \frac{[\text{CO}_2]_{\text{intake}} - [\text{CO}_2]_{\text{ambient}}}{[\text{CO}_2]_{\text{exhaust}} - [\text{CO}_2]_{\text{ambient}}}
\]

Increase in EGR ratio suppresses the rapid burning during premixed combustion and consequently reduces NOx formation. NOx can be reduced almost in proportion to the EGR ratio and that an approximately 50% NOx reduction at a 20% EGR ratio can be achieved without much emission of smoke and unburned HC emissions. Diesel engines admit into the cylinders as much air as it is practicable to trap at a given engine running condition. Thus, the application of EGR involves displacement of some of the inlet air by EGR. Because of this air displacement, there is a reduction in the air available for combustion. Since for a given torque and power output, the amount of fuel supplied to the engine must be constant, the reduced air available for combustion lowers the air fuel ratio at which the engine operates. This reduction in air fuel ratio can affect exhaust emissions substantially. When EGR is mixed with the inlet air supplied to a Diesel engine, the temperature of the inlet charge to the engine increases, which can significantly affect the compressed charge temperature and the combustion process. As diesel engines operate with the airflow unthrottled at part load, the CO₂ and H₂O concentrations in the exhaust gas are low. Because of this, high EGR levels are required for significant reductions in NOx emissions. Fig 4 shows how NOx concentrations decrease as a DI diesel engine inlet air flow is diluted at a constant fueling rate. The dilution is expressed in terms of oxygen concentration in the mixture after dilution.

Fig.4 Effect of reduction in oxygen concentration by different diluents (EGR, CO₂, N₂) on NOx emission in DI diesel engines are mainly affected by two factors, the presence of oxygen in the charge and the reaction temperature, which promotes chemical activity during both the formation and destruction stages. During the formation stage, the reaction temperature is close to the adiabatic flame temperature, which is a consequence of the oxygen concentration in the charge, the initial temperature and pressure and the local fuel air ratio. EGR reduces the oxygen concentration in the charge and, consequently, the combustion pressure and temperature.
There are mainly two problems in using the EGR technique in diesel engines, increased soot emission and introduction of particulate matter into the combustion chamber. Particulate matter abrasion may occur when these high velocity particulate matter come in contact with the cylinder components. Therefore, there is a necessity to use these EGR with particulate trap. Because, pores of the particulate trap may clog in regular use, there should be regeneration process for the particulate trap for proper functioning. In another experiment, exhaust gas temperature have been observed with different EGR rate. The experiment was conducted in a two-cylinder constant speed diesel engine generator set. Fig 5, fig 6 shows the results of the experiment.

![Fig. 5 Exhaust gas temperature vs load at constant EGR](image1)

![Fig. 6 Thermal efficiency vs load at constant EGR](image2)

Fig.5 Exhaust gas temperature vs load at constant EGR [3]

Fig 5 shows the variation of exhaust temperature with load at different EGR rates. It is clear from fig 5 that the exhaust temperature is decreasing at constant load. It is well known that the most important reason for the formation of NOx in the combustion chamber is extremely high temperature. Experimental results indicate (Fig. 5) a decrease in the exhaust temperatures with increasing EGR, therefore it can be safely concluded that the combustion chamber temperatures also decrease and thus the formation of NOx is decreased. Fig 6 shows that this increase in temperature does not affect the thermal efficiency of the engine, however, at high loads and at high EGR rates, thermal efficiency decreases slightly.

From the above discussion, it is clear that the application of EGR produces some sideeffects on the performance of diesel engines. EGR includes worsening specific fuel consumption and particulate emissions. In particular, EGR should run optimally so that proper control must be there in NOx and particulate emissions, especially at high loads. The application of EGR can affect adversely the lubricating oil quality and engine durability [2]. Also, EGR has not been applied practically to heavy duty diesel engines because wear of piston rings and cylinder liner is increased by EGR. It is considered that sulfur oxide in the exhaust gas strongly relates to the wear. Studies showed that the sulfur oxide concentration in the oil layer is related strongly to the EGR rate [2], inversely with engine speed and decreases under light load conditions. It was found that as the carbon dioxide levels are increased due to EGR, the combustion noise levels also increase, but the effect is more noticeable at certain frequencies. Furthermore, whatever the carbon dioxide content of the intake mixture, it has been observed that as the engine load is increased, the noise levels decrease.

V. Conclusions

Diesel exhaust contains CO2, H2O, N2 and O2 in thermodynamically significant quantities and CO, HC, NOx and soot in thermodynamically insignificant but environmentally harmful quantities. In modern Diesel engines, the combination of the former quantities normally comprise more than 99% of the exhaust, while the later combination, the pollutants, accounts for less than 1% in quantity. Thus, the challenge is to minimize the pollutants by manipulating the thermodynamic properties and the oxygen concentration of the cylinder charge whilst
keeping minimum degradations in power and efficiency, which is the principal reason to apply Diesel EGR. Although EGR is a very good technology for controlling the NOx emission but soot concentration and TAN (Total acid number) increases in the combustion chamber using EGR. This increased soot concentration and TAN may damage the engine component by wear and corrosion rapidly. Exhaust temperature decreases with the increased EGR rate for constant load condition. It means the peak temperature is also lower in combustion chamber, which reduces NOx emission.

**Nomencature**

NOx - Nitrogen oxide, NO- Nitric oxide, HC-Hydrocarbon, CO-Carbon monoxide, CI-Compression ignition, NO2-Nitrogen dioxide, NH3 -Ammonia, Pt-Platinum, HCN-Hydrogencyanide, O2 _Oxygen, H2 _Hydrogen, N2-Nitrogen.

**References**