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Effect of EGR on Performance and Emissions of C.I Engine Operated on Alternate Fuels: A Review

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Abstract—*Increasing environmental concern and stringent emission norms are alarming the situation to look for appropriate emission reduction technologies. Out of various technologies, exhaust gas recirculation (EGR)is found to be a prominent tool to reduce and control the oxides of nitrogen (NO_X) emissions. This paper focuses on the effect of EGR technique on C.I engines fueled with different alternative fuels i.e. Biodiesel (karanja, jatropha), CNG.EGR lowers oxygen availabilityin the combustion chamber which reduces flame temperature. Application of EGR in diesel engine causes higher soot emissions. It leads to other engine problemslike degradation of lubricating oil, higher carbon deposits and enhanced engine wear which are not favorable in long term engine running. It is found that application of EGR significantly reduces NO_X emissions with slight increase in other emissions like CO, HC and PM. However, with the variation in EGR% they can be controlled up to an extent. No significant variation in performance was reported by most of the authors. In order to counter the adverse effects of EGR, people have suggested to use augmented technologies along with EGR like DOC and DPF. Moreover, biodiesel blends are also found to be in good relationship with EGR from emissions point of view. Use of biodiesel with EGR results in lower CO and HC exhaust emissions. The loss in BTE could be overcome by increase in injection pressure and optimized injection timing for biodiesel fuel. Overall it is concluded that use of EGR with biodiesel could be a prominent solution for increasing environmental pollution arose due to diesel engines.*

Keywords: *Exhaust gas recirculation, Hot EGR, NO_X emission, smoke, biodiesel blend, injectionpressure*

1. INTRODUCTION:

Diesel engines are widely used because of higher thermal efficiency, lower fuel consumption, lower carbon monoxide (CO) and hydrocarbon (HC) emissions, etc. However, environmental issues have become increasingly prominent with the increment of diesel engines ownership. NOx emitted from diesel engines is increasingly injurious to human health and the environment such as photochemical smog and acid rain. As a result, many countries have enacted more stringent regulations to reduce it[1].

Although, major constituents of diesel exhaust include carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), and oxygen (O_2); carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), and particulate matter (PM) are present in smaller but environmentally significant quantities. In modern diesel engines, first four species normally consist of more than 99% exhaust, while last four (the harmful pollutants) account for less than 1% exhaust. NO_x comprises of nitric oxide (NO) and nitrogen dioxide (NO_2) and both are deleterious to humans as well as environmental health. NO_2 is more toxic than NO. It affects human health directly and is precursor to ozone formation, which is mainly responsible for smog formation[2].The principal source of NO is the oxidation of atmospheric nitrogen. NO_X is formed during thecombustion duehigh temperature[3]. The different methods are available for the reduction of NO_X. The cetane improvers can reduce NO_x but the addition of cetane improvers increase the cost of fuel andthe possibilities of auto oxidation. Retarded injection is themethod used for reduction in NOx for Compression ignitionengines, but the method leads to increase in Brake specific fuelconsumption and emissions. Water injection leads to corrosionand increase in the weight due to water storage[4].The exhaust gas recirculation (EGR) technique is gaining widespread use as one of the most efficient methods or technique for reduction of nitrogen dioxide (NO_x). This involves the circulation of part of the exhaust gas along with the intake fresh air charge, into the combustion chamber of the diesel engine for combustion together with the fuel injected in the normal power cycle of the diesel engine. EGR is an emission control system which allows significant reduction in NO_x gases in almost all types of diesel engines including Light Duty, Medium Duty and Heavy-Duty engine use orapplications, and primary engines as low as two strokeas used in marine operations andapplications[5].

To studythe effects of EGR on the performance and emissions of automotive engines, the system shown in Fig. 1 gives an example of the EGR system.

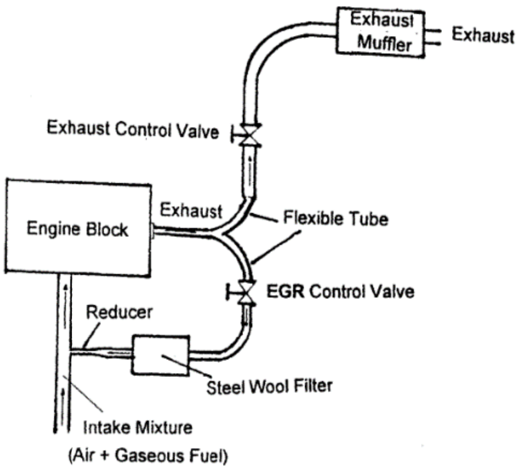

Figure 1 EGR system[6]

There are two ways to use exhaust in engine cylinder i.e. externally and internally. Use of variable valve timing (VVT)or other mechanisms to retain a certain fraction of exhaust from a preceding cycle is known as Internal EGR. whereas in external EGR the arrangementof external pipe could help to usse exhaust by means of the pressure differential between the exhaust gas and inlet air.

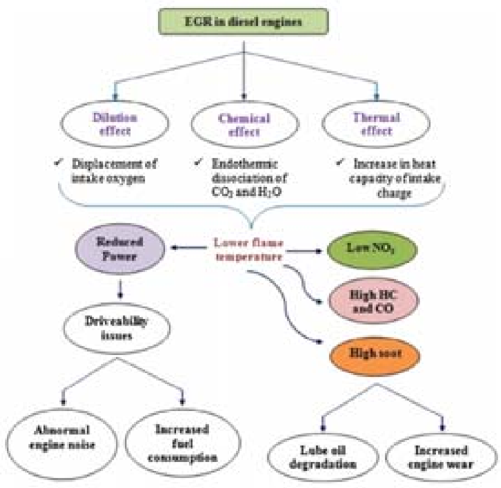

Figure 2: Effects of EGR on diesel combustion and pollutant formation[7]

To suppress NOx formation some of the fresh air is displace by EGR which is act as a heat sink. The higher heat capacity of these diluents results in lower combustion rate and temperature rise, which reduces the peak cylinder gas temperature. A pictorial representation of the EGR effect on diesel combustion is provided in fig. 2 [7]. When a part of this exhaust gas is re-circulated to the cylinder, it acts as a diluent to the combustingmixture. This also reduces the oxygen concentration in the combustion chamber. The specific heat of exhaust gas is much higher than that of fresh air. Hence EGR increases the specific heat of the intake charge, thus decreasing the temperature rise for the same heat release in the combustion chamber[8].With EGR, the mean specific heat capacity of the engine inlet charge will be higher compared to that of air. This rise in specific heat capacity value is due to both carbon dioxide and water vapor having higher heat capacity values than nitrogen and oxygen. This rise in the mean specific heat capacity of the inlet charge will called the thermal effect of EGR [9].

When EGR is applied, the engine intake consists of fresh air and recycled exhaust. The percentage of recycled gases is commonly represented by an EGR ratio, i.e. the mass ratio of recycled gases to the whole engine intake. The fresh air intake contains negligible amounts of CO2 while the recycled portion carries a substantial amount of CO2 that increases with EGR flow rate and engine loads. Notably, CO2 is merely a combustion product. Thus, it is intuitive and practical, to measure EGR ratio by comparing the CO2 concentrations between the exhaust and intake of the engine [10].

EGR rate = $100 \times (m_{EGR}) / (m_{air} + m_{EGR})$[11]

EGR rate = $100 \times (V_{EGR})/(V_{air}+V_f+V_{EGR})$[12]

EGR rate = $100 \times (Q_{without\ EGR} - Q_{with\ EGR})/Q_{without\ EGR}$

EGR rate = $100 \times ([CO_2]_{intake} - [CO_2]_{ambient}) / ([CO_2]_{exhaust} - [CO_2]_{ambient})$ [13]

2. EFFECT OFEGR ON ENGINEPERFORMANCE

There are so many studies have been done on hot EGR and it has been reported that the EGR effected the performance and combustion characteristics. The variation of BTE with load for diesel operated engine at constant speed is lower at all loading conditions when operated with EGR and compared to without EGR[14].As increase in EGR percentage the BTE decreasesmarginally.The possible reason may the oxygen deficiency at higher load,which leads to incomplete combustion[15].Another experiment done on Diesel - piloted biogas engine and found thatas the engine load increases the brake thermal efficiency increases. EGR up to about 20% the BTE has increase and then startsto fall. This is because of re-burning of HC that enters combustion chamberwith the recirculation of exhaust gases and EGR increases intake charge temperature which increases therate of combustion. It is observed that BTE is deceases if the too much of exhaust gas is recirculated this is due to the higher Exhaust replaces the too much of oxygen [16].

An experiment conducted with jatropha curcas biodiesel on C.I. engine with varying load, injection pressure, biodiesel blend percentage and EGR rate and investigated the performance of brake thermal efficiency. The experimentation with 300 to 500 FIP for 75% and 100% load and the addition of blends B10, B20 has improved the BTE without EGR. Biodiesel containsoxygen which helps in better combustion which result into higher efficiency. A slight increase in BTE is observed when EGR rates of 15% is applied for blends B10 and B20 at 75% and 100% load with same condition of 300 bar FIP. 6.6% higher efficiency is obtained when operated at B20 at 15% EGR with 75% load and 300 bar FIP conditions as compared to diesel engine. This increase in efficiency is due to the re-burning of the hydrocarbon which mix with fresh air and goes into combustion chamber via intake manifold.The maximum improvement in performance isobserved is 9.12% at full load(500 bar FIP) for B20 blend with 15% EGR in comparison with diesel fuel[17].

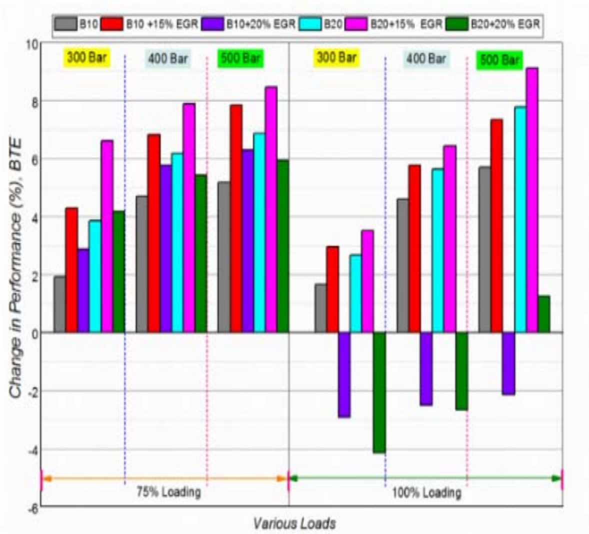

Figure 3 BTE 75% and 100% loads at 300,400,500 FIP[17]

The experiment performed using diesel and different blends of jatropha biodiesel fuel withEHN (ethyl hexyl nitrate) as cetane improver with a variation in % mass fraction of EGR.The BTE is found tobe increasing with the increase in biodiesel at a fixed EGR% and there is an increase in the rate of BTE at50% load when compared to full load. Since at full loadoxygen deficient operation under EGRisresponsible for marginal increasein BTE. The increasein BTE with the increase in the percentage of EGR is due tothe increased combustion velocity, as EGR increases theintake charge temperature[18].

The BSFC and BTE are both depended on each other if one increases than other decreases and vice versa. As the injection timing is advanced from 19to 27BTDC, for CNG–HOME fuel the BTE increases for 80% and 100% loads. This is due to the available time of burning for CNG fuel is more. The engineperformance was smooth, andthe ignition delay reduced through the advanced injectiontiming but tended to incur a slight increase in fuelconsumption. At 100% load, the BTE islowercompared with 80% engine operation. Animprovement in BTE was achieved by advancingthe injectiontiming. Maximum pressure andpressure rise rate are higherfor the advancedinjection timing[19].

Temperature of exhaust gas was observed to be lower in case EGR operated engine. The possible reason for this temperature reduction may be stated as relatively lower availability of oxygen molecule and higher specific heat of intake diluents[20]. The lower EGT with EGR rate signifies reduction of NOx emission. As the EGR rate increases the volumetric efficiency decreases. The mass flow rate of intake air reduces because of EGR implementation the mixed intake air temperature increases and thus the density of air will decrease,and volumetric efficiency drops [21][22].

3. EFFECT OFEGR ON ENGINE EMISSIONS

DOC, DPF, SCR, and EGR are some of the pre-treatment/ post-treatment systems designed to treat the exhaust gases of diesel engines, especially PM and NOx.The three major causes of formation of NOx are high combustion temperature, availability of excess oxygen, and duration of availability of excess oxygen.EGR, a widely used pre-treatment technique, reduces NOx emissions from diesel engines by lowering oxygen concentration and flame temperature of the working fluid in the cylinder.As the EGR rate increases the NOx emission decreases in diesel engine. At lower load percentage of NOx reduction is higher than that of higher load in diesel engine[23].The reduction of oxygen availability due to the displacement of some of the oxygen in the fresh intake air charge by the recirculated exhaust gas. This causes a reduction in the local fame temperature because of the spatial broadening of the fame due to the reduction in the oxygen molar fraction. Also, there is the thermal effect due to the increase in the average specific heat capacity of the gases in the combustion zone, since the recirculated exhaust gas contains CO_2 and H_2O with higher specific heat than that ofair. Finally, there is a reduction in the combustion temperature due to endothermic chemical reactions, such as $CO_2$and H_2O dissociation [24].NO_x emissions for the conventional diesel engine were higher than the dual fuel engine operated with JOME and CNG at lower and intermediate loads. This was because of the higher in-cylinder temperature in theconventional diesel engine.At higher load, due toimprovement in gaseous fuel utilization, higher incylinder temperature and extra availabilityof oxygen in JOME increases NO_x emissions in the dual fuel engine. Hence, at high load, thedual fuel engine emitted higher NO_x compared to the conventional diesel engine[25].

It is noticed that CO_2, CO and THC emissions increase with the increase of EGR rate.This trend isexplained by the fact that the fresh intake air contains negligible amounts of CO2, while the EGR fraction carries a substantial amount of CO_2, which is increased with EGR flow rate and engine load. This increment becomes more relevant for higher EGR rates and engine loads[26]. Percentage of CO emission for diesel fuel has linearly increased overall 6.2% due to increasing engine speed when running with EGR. While in palm-biodiesel, it is found that CO emission has increased to a 9.2% corresponding with theincreasing engine speeds under EGR mode.Percentages of CO emission from palm-biodiesel were higher than diesel when operating with EGR due to the some of the oxygen present in the inlet charge is replaced with recirculates exhaust gas that causes incomplete combustion. Furthermore, the increasingcetane number in palm-biodiesel helps to reduce the CO concentration in the exhaust piping.It was illustrated that palm-biodiesel has the highest rate emitting UHC with nearly 12% as compared to conventional diesel when operating with EGR due to thereduction of oxygen in the inlet charge, replaced by higheramount of carbon dioxide (CO_2) into thecylinder. It was demonstrated that CO_2 emissionwas increased when operating with the increasing engine speeds with palm-biodiesel with 9.4% underEGR mode[27].

CO emissions from sunflower methyl ester biodiesel blend with EGR and without EGR inC.I. engine is investigated and noticed thatthe CO increases with increase in load and EGRrate.However, CO emissions of SFME were comparativelylower. Higher values of CO were observed at full load forboth diesel and biodiesel fuels with EGR. For biodiesel,the excessoxygen content is believed to have partiallycompensated for the oxygen deficient operationunderEGR. Dissociation CO_2 to CO at peak loads where highcombustion temperature and comparatively fuel richoperation exists, can also contribute to higher CO emissions[28].

The particulate matter(PM) is basically composed of soot and accounts forthe smoke. The formation of opaque smoke ensuesunder the air deficit conditions which locally exist inthe engine cylinder and increases as the air/fuel ratiodeclines. Smoke emission increases as the EGR% increases in diesel engine. Higher rate of increase in smoke emission was found at higher loads. This may be due to the reason that the charge becomes richer in fuel at higher load. The KOME and its blends showed slight reduction in smoke emission due to oxygen enrichment. The B50 and B100KOME showed an average reduction of 7.17 and 11.8 % in smoke emission compared withneat diesel fuel[29]. Soot emission during combustionfor various n-butanol–diesel blends at different EGR rates are investigated and noticed that as butanol contentincreases in the blends results in the reduction of soot due to a higher oxygen/carbon ratio[30].

4. EFFECT OF EGR ON ENGINE PARTS

Figure 4shows the physical conditions of various vital engine partslike cylinder head, injector tip, and piston crown respectively of engine operated with EGR (a) and without EGR (b)on which carbon deposits take place due to the direct expose to the combustion in-cylinder liner. Engine operated with EGR have the higher Carbon deposits on the variousparts of the engine rather than the engine operatedwithout EGR[31].

Figure 4 Carbon deposits on engine parts [31]

Engine parts give a qualitative estimation of amount of soot generation inside theengine by means of soot deposits on it andit was observed that the normally operatedengine has lower soot emission as compared toengine operated with EGRsystem [32].It has been observed that using EGR the extent of wear of top ring in theengine is lower than normal operating engine. This may be due to the lower temperature of thecombustion chamber of the engine using EGR. However, using EGRthe second and third compression ring and oil ring iscomparatively having the higher wear rate. This may be due to the presence of higheramount of soot and wear debris in the lubricating oil as compared tothe engine using without EGR [33].

5. CONCLUSIONS

- For reducing the NOx emission EGR is a very useful technique for diesel fueled C.I. engine with slightly compromising with the efficiency and other emissions.
- The recirculation of exhaust gas to the combustion chamber displaces the oxygen content in intake air.
- Exhaust gases lower the oxygen concentration in combustion chamber and increase the specific heat of the intake air mixture, which results in lower flame temperatures.
- The emissions and performance of C.I. engine gets affected differently by lesser flametemperature and reduced oxygen content.
- In diesel engine at lower load the brake thermal efficiency can be marginally decrease or remain unaffected by increasing in EGR% up to 20%.

- Normal trend of brake thermal efficiency in diesel fuel operated engine is as increase in EGR% up to 30% the BTE will reduced slightly.
- Diesel fueled C.I. engine will cause slightly more CO and HC but higher smoke emissions with significant reduction in NO_x emission.
- 20% EGR can be used for reduction in NO_x emissions in diesel engine with approximately same BTE but slightly increase in HC & CO with higher smoke emissions
- For CO, HC & Smoke reduction biodiesel blends can be used with EGR which reduces all three emissions compare to diesel operated engine
- SFME blend B20 and 15% EGR rate culminates into NO_x reduction (25%) and HC & CO emissions decreased by 5% and 10%.
- But use of biodiesel blends will lead to decrease in BTE and increase in BSFC compare to dieselfueled engine
- For increasing the BTE the injection pressure is increased, and it is found that the HC, CO & Smoke emissions also reduced but penalty in NO_x emissions as compared with the standard injection pressure with EGR in C.I. engine
- Reduction in emission as well as improvement in performance were found in combination of biodiesel blend (B20) with EGR (15%) and FIP (500bar)

With the use of EGR system, amount of carbon deposition on various parts of engine has increased significantly

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