A Review on Performance and Emission of CI Engine using Exhaust gas recirculation (EGR)

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Abstract. The diesel engine has the advantage over gasoline engine due to its low fuel consumption, higher combustion efficiency, durability and low hydrocarbons (HC), particulate, carbon dioxide (CO₂), carbon monoxide (CO) and NOₓ emission as a major source. Due to abovesaid problems, diesel is now blended with Biofuels and play a significant role to meet its energy and environmental challenges. Exhaust gas recirculation (EGR) is an eco-friendly alternative to lower NOₓ and particulates emission. The use of EGR in compression ignition engines, lowers the concentration of oxygen mixture and flame temperature. However, it has been observed that advantages of EGR is fuel specific. In present paper a performance review of compression ignition engine using EGR with blended fuels has been carried out. The effect on break power, break specific fuel consumption, thermal efficiency has been reported. Further aspects of response surface methodology on optimization of NOₓ emission, smoke opacity and BSFC has been carried out using blended fuel, EGR rate, injection timing etc.

1. Introduction

Due to depleting problems of fossil fuel resources and harmful exhaust emission of greenhouse gases and NOₓ from CI and SI engine, there is need of alternate sources of fuel and new technologies to meet the requirement. In order to growing environmental concern, diesel is now blended with other Biofuels (Dual fuelled s). The use of dual fuel has advantages over CI engines operating on diesel fuel alone. Engine operating on dual-fuel, can use various fuels to meet current and future problems. The operation of such engine is based on the interaction of two fuels containing different reactivity level. Biodiesel is produced from both edible and nonedible substances and has advantages in view of current environmental and energy concerns having psychochemical properties and combustion characteristics similar to conventional fuel. It has been reported that use of vegetable oils (i.e. corn, canola, soybean, peanut, rapeseed, jatropha, olive oils, palm oil, coconut and rubber seed) have advantages like low level of sulphur, higher oxygenated nature, higher cetane number and produce less toxic emission[1]. Knothe et al. [2] have reported that vegetable oils have a better lubrication property and a higher ignition temperature than the Diesel fuel and their application are based on
geographical and climate conditions. Song et al. [3] have observed the higher percentage in increase of NOX in exhaust gases with increase of oxygen during combustion rather than the use of fuels enriched with oxygen. Lapuerta et al. [4] have found that because of stoichiometric combustion, there is insignificant increase in NOX emission in biodiesel. In typical biodiesel, stoichiometric combustion found to be occurred at the oxygen-fuel ratio of 2.81, whereas for a standard diesel this ratio is about 3.58.

Various researchers have reported the performance and emission characteristics of engine using biodiesel. It has been observed that reduction in NOX deteriorates the fuel economy and performance of the engine. It has also been found that comparative thermal efficiency of diesel engine using diesel is higher than the other techniques, but high-level emission of NOX, smoke and soots are key problems. Some authors [5-7] have reported that with use of biodiesel, the performance of the engine power decreases because of higher viscosity and low heating value. Jinlin X. et al. [6] have reported more formation of NOX in bio diesels as they contain more oxygen content and having higher cetane number. At higher load, engine operates on dual fuel mode show better results in respect of specific fuel consumption and efficiency than the engine operates on diesel fuel alone, but with increase NOX exhaust emission. However, at low and medium loads, high specific fuel consumption and lower energy efficiency has been reported. To improve the thermal performance and lowering of NOX of the dual fuel engine, particularly at low and medium loads, EGR system has been operational. Researchers have found that EGR techniques reduce emission of NOX, as it leads to reduction of oxygen content of the mixture and reduced the combustion temperature below 1371°C. However, operating points need to be decided by three parameters i.e. % engine load, diesel substitution rate and EGR rate.

As the combustion of mixture with the use EGR is not happened properly, causes formation of excess soot. The higher soot emission leads to degradation of lubricating oil, more carbon deposits, and enhanced wear on engine parts. It has been reported that due to high specific heat of CO2 in EGR, peak cylinder temperature gets reduced. Due to better combustion, rate of pressure rise at various loads is higher if hot EGR system used, compared to cooled EGR technique. Divakar et al. [8] have carried out Real-time model computation to analysed the attainment of ultra-low NOX emissions at various loads and boost set-points at controlled EGR effectiveness. Daisho Y et al. [9] have reported that with the use of cooled EGR, the combustion noise and NOX % may be decreased. Walke et al. [10] have found with higher EGR, the NOX level decreases significantly with slight increase in BSFC and smoke opacity.

The operating conditions for particular fuel with optimized EGR rates may not fit well with the other fuel because of change in chemical properties of each fuel under similar working conditions. Kumar et al. [11] reported the effect of increase in compression ratio (CR) and found in increase brake thermal efficiency and decrease in specific fuel consumption. As the EGR percentile increases, at different compression ratio, there is decrease in pressure rise rate and thermal efficiency, whereas NOX emission increases from 11% to 85%. Mohamed [12] has reported that to reduce the combustion noise and emission of NOX, 5% EGR is favourable. Kumar et al. [13] have reported that fuels like gasoline, di-methyl carbonate (DMC) and alcohols in CI engines produced difficulty because of low cetane number, low calorific value, high volatility and latent heat of vaporization. However, these fuels can be used suitably when blended with diesel [14]. Saleh [15] has found that with the use of 5% EGR at part load, the performance of LPG-diesel engine (with 70% propane in LPG) improved. Poonia and Mathur [16] have studied the effect of EGR and load on LPG-diesel engine and observed that variation in peak pressure and indicated mean effective pressure in cycle are lower up to 60% of load compared to engine operating without EGR. Poonia and Mathur [17] have reported the insignificant effect of hot EGR on combustion delay whereas cold EGR increases. Rajan et al. [18] have carried out the study using sunflower methyl ester as fuel using EGR technique on a DI engine. They observed that 15% EGR reduced the NOX emission and smoke by
25%. Wagner et al. [19] have used highly diluted intake mixture and found that at 44% EGR, there is sharp decrees in PM emission with a drop in NOx, however affect the fuel economy significantly. Vallapudi et al. [20] have carried out combined effect of EGR and injection pressure on NOx emission using tamarind seed biodiesel blend. They have reported that 10% EGR at 220 barslower the NOx emission by 80.5% of standard conditions with insignificant decrease in performance. Kumar and Kumar [21] have reported the effect of EGR using Jatropha oil methyl ester as the pilot fuel for compressed natural gas on dual fuel engine with variable load and reported improve in performance and emissions characteristics, at low and intermediate loads. Raju and Kishore have reported 45.67% reduction of NOx with tamarind seed methyl ester (TSME 20) at 20% EGR as compared to diesel fuel with TSME 20 (52.69%). However, there is a slight reduction in brake thermal efficiency [22].

Performance of an CI engine with EGR may be enhanced by optimizing the design and operating parameters. In this review, influence of exhaust gas recirculation on combustion characteristics and performance of diesel engine (both single and dual fuel mode) has been carried out. The comparative application of EGR on blends of high n-butanol, n-pentanol with diesel, Palm-Biodiesel, Cottonseed Biodiesel fuel etc. at various conditions have also been reported.

2. Classification of EGR system

Figure 1 shows the schematic of EGR system. EGR systems have been classified as under;

2.1. Based on temperature
   (a) Hot EGR (b) Partly cooled EGR and, (c) Fully cooled EGR.

2.2. Based on configuration
   (a) Long route and, (b) Short route.

2.3. Based on pressure
   (a) Low pressure system and, (b) High pressure system.

In hot EGR cycle, some exhaust gas recycled back to intake directly. Whereas, in cooled EGR system re-cycled exhaust gas is pre-cooled. The engine using hot EGR promote better combustion with increase in thermal efficiency. The volumetric efficiency increases with cooled EGR with decrease of NOx, however unburnt hydrocarbons increases in exhaust.

![Figure 1. Schematic of EGR Diesel Engine.](image)

The % EGR is calculated using the Eq. (1)

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

(1)
3. Performance and emission characteristic of EGR engine

Performance of CI engine using EGR is influenced by speed, percentile of blend, load, fuel quantity, injection timing, fuel compositions, engine speed, SOI advance, EGR % etc. The results presented by some authors as effective measures for further improvement in performance taking into various parameters, are as under;

3.1 Effect of EGR on diesel fuel

Agrawal et al. [23] carried out experimentation on air cooled two-cylinder diesel engine of rpm 1500 using diesel fuel, EGR rates (0-20%) and observed that:

(i) NOx emission reduced substantially at 15% EGR without deteriorating the BSFC, thermal efficiency, and emissions.
(ii) Increase rate of EGR reduces NOx. However, performance decreases at higher loads. The effects of EGR change on thermal efficiency and BSFC is insignificant at higher engine load.
(iii) There is more wear of piston rings due to higher carbon deposits on the engine parts.

Chowdary et al. [24] carried out experimentation on constant speed single cylinder CI, with different EGR rates (0-10%) and advanced start of ignition (SOI) from 11° bTDC to 14.5° bTDC and following have been observed:

(a) Effect of EGR (10%) with SOI 11 degree

NOx increases significantly with increase in crank angle from 0-32° and remains nearly constant further till 150° crank angle. SOI 11° & EGR 10% has reduced the emission of NOx by 34.4%. whereas there is decrease in cylinder peak pressure about 0.30 MPa and increase in soot by 37.2%.

(b) Effect of SOI only (11-14.5 Degree with EGR 0%)

NOx increases with 7.4% with increase in SOI advanced by 3.5 degree. Soot increases by 37.2% but decreases at the end of combustion about 52% with advanced SOI. Further there is increase in peak cylinder pressure with advanced engine.

(c) Effect of SOI 14.5° with EGR 10% compared to SOI 11° with 0 EGR

NOx decreases about 1.2% at the end of combustion, Peak pr. increases by 0.8 MPa and decrease of soot at the exhaust by 21.3%.

3.2 Effect of EGR on Neat palm-bio diesel blend

Yasina et al. [25] carried out experimental analysis using neat palm-bio diesel blend on water cooled diesel engine (four stroke), operating at variable 1000-3000 rpm and observed that;

(i) Brake power increases with RPM up to 2500 rpm. However, the effect with B100 is less with increase EGR as compared to Diesel fuel. Further, torque decreases with increase in RPM and with B100 with increase EGR.
(ii) BSFC increases with rpm and EGR and higher than Diesel. Emission of CO, CO2 and UHC increases with RPM and higher with B100 than Diesel.
(iii) With increase in engine speed, NOx emission is less using EGR when operating with B100 fuel than the use of diesel only.

3.3 Effect of EGR on Cotton seed Bio diesel blend

Sakharea et al. [26] carried out an experimental work, using cotton seed Bio diesel blend on single cylinder fixed rpm (1500) CI engine with variable EGR (4-6%). It has been observed that;
(i) Biodiesel (B20) an oxygenated fuel has shorter ignition delay as compared to diesel due to higher cetane number. The decreased in ignition delay has been recorded from 8 °CA to 7 °CA with 6% of EGR compared to diesel fuel alone.

(ii) With use of Diesel fuel, BSFC increases from 7.69 % (4 % EGR) to 11.53 % (6 % EGR) compared to use of diesel fuel alone. Whereas there is increase of BSFC from 30.76 % (4 % EGR) to 42.60 % (6 % EGR) using B20 biodiesel in comparison to diesel fuel.

(iii) At the rated load, thermal efficiency decreases from 1.33 % (4 % EGR) to 3.9 % (6 % EGR) in comparison to use of diesel fuel alone. Whereas there is decrease in thermal efficiency from 4.95 % (4% EGR) to 5.1 % (6 % EGR) using B20 biodiesel in comparison to diesel fuel.

(iv) Decrease in emission of CO and UHC is higher with increase EGR using B20 biodiesel in comparison to diesel fuel. However, NOx level in exhaust is higher in comparison to base diesel and decreases with increase in EGR.

3.4. Effect of EGR on diesel-chaulmoogra oil - diethyl ether blend
Krishnamoorthi et al. [27] reported experimental work on variable speed CI compression ignition engine at 1500-2100 rpm, using diesel-chaulmoogra oil diethyl ether blend, EGR varies from 0, 5 & 10% and optimization using ternary blend i.e. for 65% diesel+ 25% straight vegetable oil + 10% diethyl ether blend. It has been observed and concluded that:

(i) Optimum values of the blends determined as 0% EGR (80% load), 5% EGR (77% load) and 10% EGR (73% load). maximum thermal efficiency of 28.85% has been observed with 10% EGR, 20.6 compression ratio and 1500rpm with 100% load. However minimum BSFC (0.52 kgkW⁻¹hr⁻¹) has been found at compression ratio of 19.2 and at 1800 rpm, at full load and 5% EGR.

(ii) At high compression ratio and speed at full load with 10% EGR, engine produced maximum smoke with higher NOx emission at 1500 rpm. Maximum UHC emission of 47.7 ppm has been observed at compression ratio of 17 and 1500 rpm at 25% engine load with 10% EGR.

3.5. Effect of EGR on diesel and CNG
Selim [28] reported effect of EGR (5-15%) on single cylinder indirect injection CI engine with variable compression ratio and speed (1200-2400 rpm) as under:

(i) Efficiency increases with increase in the speed from 1200 - 2400 rpm. Increase in efficiency is less significant with increase in EGR ranges up to 5% for low speed (1600 rpm). It has been further observed that with increase in EGR from 10 and 15%, the thermal efficiency tends to decrease irrespective of engine speeds.

(ii) 5% EGR is favourable to increase the thermal efficiency, reduction of combustion noise and NOx emission.

4. Optimization of Exhaust Gas Recirculation System
Response Surface Method is a useful technique, for optimizing output responses obtained with the change of fuel, EGR, injection timing etc. The experimental data recorded are further analysed using regression and polynomial models. In order to solve multi response problems and to get optimum combination RSM along with the desirability approach is used effectively with blended fuel with reasonable accuracy. The optimization effects reported by some researchers using EGR for various responses are:

Kumar et al. [29] carried out experimental work using three types of blends namely dimethyl-carbonate (DMC), isobutanol and n-pentanol on direct injection CI engine, varying the EGR as 0, 15, 30%, high-load condition and injection time change 21, 23. 25° CR bTDC. In order to minimize
NOX and smoke emission and simultaneously BSFC, the EGR rate had been optimized with injection timing and observed that;

(i) The point of high EGR rate and small injection timing is best suitable condition to minimize NOX emissions and found to be higher with the use of n-pentanol blend with diesel compared to blends of Isobutanol/diesel and DMC/diesel. Further with retard of injection timing from 25° to 21° bTDC and increase EGR rate, NOX emission decreases possible due to lower combustion temperatures irrespective of blends.

(ii) The advanced injection timing and low EGR rate produce best smoke opacity. Smoke opacity decreases to greater extent with blend of Iso butanol and diesel in comparison to use of blends of DMC/diesel and n-pentanol/diesel.

(iii) The BSFC was found lower for all fuel blends under study and observed minimum with the engine operating with blend of isobutanol/diesel.

(iv) The optimum combination is obtained with blends of isobutanol/diesel compared to diesel alone, injected at 22° bTDC under natural condition. The reduction in 12.4% NOX and 100% smoke opacity with insignificant increase in BSFC (2.9%) has been found to be optimum.

Praveena et al. [30] experimentally tested diesel engine with Mahua oil and its blends with varying EGR between 10 to 30%, injection pressures (200 & 230 bar), engine load and optimum EGR for 20% Mahua oil blend. It has been observed that:

(i) There is nearly equal brake thermal efficiency using Mahua oil blend of 20% at pressure of 200 bar, with reduction of UHC, CO and carbon particulate in exhaust. However, produces more concentration of nitrous oxide gases than the use of diesel as a base fuel alone. The aforesaid condition is observed as good agreement in view of specific fuel consumption as well as BTH efficiency.

(ii) With increase of blend proportion, emission of nitrous oxide gases increases, however reduced at higher loads.

Bhaskar et al. [31] carried an experimental study on single cylinder Diesel engine using Fish oil methyl esters (FOME) and its blends, EGR 10, 20, 30% at 20% blend, constant RPM of 1500 and Diesel, FOME & their 20-80% blend were used. It has been observed that:

(i) The brake thermal efficiency is found to be lower all brake power outputs, compared to diesel fuel and observed to be decreased with increase in blend %.

(ii) At all loads, emission of CO, UHC and soot using FOME/ blends is lower, which decreases further with increase in blend percentage. The optimum value brake thermal efficiency has been obtained with 20% blend in comparison to diesel.

(iii) Percentage increase in NOx emission has been reported with increases of FOME %. NOX emissions were decreased by employing exhaust gas recirculation and reported optimum with 20% blend at 20% EGR rate considering emission of NOx and soot.

Gaikwad et al. [32] reported an experimental study on water cooled single cylinder diesel engine using blend of diesel/LPG at varying EGR rate (i.e. 5%, 10% and 15%) and load (25 to 100%). It has been observed that at 25% load, change in BTE is insignificant. At 50% to 75% load, a slight increment in the BTE is obtained with EGR and it increases with EGR rate. Slight reduction in BTE is observed with EGR at full load and it decreases with EGR rate but higher than straight diesel operation.

Comparative study has been performed on two dual fuel diesel engines at full load conditions, one operates with LPG (LPG of quantity 60% energy share is fumigated with intake air stream at ambient pressure and the diesel is injected by traditional way with injection) and another with Mahua oil blend of concentration 20% in EGR at injection pressure of 200 bar with view point to compare
NO\textsubscript{X} emission and BTE. The comparative results are plotted in Fig. 2. It has been found that there is significant decrease in the emission of nitrous oxide gases using Mahua blend compared to the use of LPG dual fuel engine. However, decrease of NO\textsubscript{X} with EGR is not much significant with the use of Mahua blend as compared to LPG fumigated engine. This may be due to lean mixture of blend produces low-combustion temperature. Emission of nitrous oxide gases NO\textsubscript{X} decreases significantly using EGR in dual fuel operation than the use of straight diesel fuel alone (970 ppm).

![Bar chart showing NO\textsubscript{X} emission and BTE with EGR for different engine loads.]

**Figure 2.** Comparative variation of NO\textsubscript{X} emission & BTE using dual fuel with EGR at full Load [27, 29].

Break thermal efficiency with use of Mahua blend has been found to be lower than CNG operated engine and decreases further with increase in EGR rate. Higher efficiency has been found if engine operates on dual fuel without using exhaust gas recirculation in comparison to use of diesels as a fuel (about 33%). This is because for higher loading condition, pilot fuel quantity increases and it led to better combustion of LPG fuel. It has also observed that BTE with Mahua blend is almost same at 20% EGR, may be due to more fuel supplied in the cylinder at higher load. However, with EGR, combustion temperature is lowered because of reduced oxygen concentration as a part of O\textsubscript{2} get replaced by CO\textsubscript{2} and some H\textsubscript{2}O.

5. Conclusions
The following results have been summarised from the review.
1. Using straight diesel as a fuel at lower loads incorporating EGR technology, there is insignificant improvement in brake thermal efficiency with decrease BSFC. However, the said efficiency and BSFC are almost remain same at higher loads. Therefore, at lower load higher EGR rate is more advantageous.

2. The NOX emission increases and soot decrease with advanced SOI. Therefore, combined effect SOI advancement and EGR is useful to reduce emission of nitrous oxide gases and carbon particulates. There is increased work output/IMEP and efficiency with combined effect.

3. Dual fuel mode without EGR gives lower emissions of NOX than straight diesel engine. When the EGR is used in dual fuel mode NOX emission decreases significantly and it decreases further with increasing EGR rate. The lower oxygen concentration decreases the peak pressure rise rate of pre-mixed combustion with decrees of combustion temperatures and pressures and, consequently, to lower NOX but increase of shoots.

4. Torque decreases with increase in RPM and EGR simultaneously decrease in Pressure rise rate.

5. BSFC increases with rpm and EGR and higher than Diesel fuel in other blended fuels.

6. Optimum performance with considerable agreement between soot and NOX emissions is obtained at 20% EGR rate with 20% blend at 100% load. However, variation is fuel specific.

7. NOX emission decreases with retard of injection timing from 25° to 21°CA bTDC and increase EGR proportion. Optimum emission of Nitrous oxide gases occurred with high EGR rate and retarded injection timing. Effect is observed significantly higher using blends of n-pentanol compared to Iso butanol and DMC in base diesel.

8. There is no major modification of CI engine required once it operates on Mahua oil and its blends. However, with increase percentage of Mahua oil, the brake thermal efficiency decreases correspondingly and found to be optimum at 20% blend with 20% EGR.

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