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Biodiesel as an Alternate Fuel in a Diesel Engine with the Cooled Exhaust Gas Recirculation—A Measure to Reduce Harmful Emissions

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Abstract - Biodiesels reduce the emissions like HC, CO and particulate matter to minimum possible extent. But the NO_x emissions increase because of the reason that the biodiesel is an oxygenated fuel. To contain this particular emission which is responsible for the human health degradation, acid rain, smog creation etc., the Exhaust Gas Recirculation (EGR) technique is resorted to. In this paper, a laboratory based DI diesel engine is run with neat biodiesel (Jatropha Methyl Ester) and cooled EGR which replaces a part of incoming air during suction. Various percentages (viz. 0%, 7%, and 14%) of EGR were practiced to investigate the effect on the engine performance and tail pipe emissions. EGR dilutes the charge in the cylinder and thus reduces the peak combustion temperatures. Lower combustion temperatures decrease the formation of NO_x with the marginal penalty of increase in other emissions. A comparison was made with the implementation of neat diesel and EGR application to consolidate the performance differences emerge in these cases. 7% EGR is proved to be the best percentage by considering both engine performance and emissions.

Key words - Biodiesel (JME), Cooled EGR, Emissions, Performance.

I. INTRODUCTION

Diesel engines are predominantly used in locomotives, large trucks and for marine propulsion. Owing to their higher thermal efficiency and lower fuel consumption, they have become increasingly attractive for smaller trucks and passenger cars also. But higher NO_x (oxides of Nitrogen) emissions from diesel engine remain a major problem in the pollution aspect. For reducing emissions, baseline technologies are being used which include direct injection, turbo-charging, air-to-air inter-cooling, combustion optimization with and without swirl support, multi-valve cylinder head, advanced high pressure injection system i.e. split injection or rate shaping, electronic management system, lube oil consumption control etc. However, technologies like exhaust gas recirculation (EGR) [1,4,5,6], soot traps and exhaust gas after treatment are essential to cater to the challenges posed by increasingly stringent environmental emission legislations.

The effect of EGR on NO_x reduction can be attributed to three theories 1) increased ignition delay, 2) increased heat capacity and 3) dilution of the intake charge with inert gases. The ignition delay theory asserts that because EGR causes an increase in ignition delay, it has the same effect as retarding the injection timing. The heat capacity theory states that the addition of the inert exhaust gas into the intake increases the heat capacity (specific heat) of the non reacting matter present during

the combustion. The increased heat capacity has the effect of lowering the peak combustion temperature. According to the dilution theory, the effect of EGR on NO_x is caused by increasing amounts of inert gases in the mixture, which reduces the adiabatic flame temperature.

With the use of EGR, there is a trade-off between reduction in NO_x and increase in soot, CO (carbon monoxide) and unburnt HC (hydrocarbons). It is indicated that for more than 50% EGR, particulate emissions increase significantly, and therefore use of a particulate trap is recommended. The change in oxygen concentration causes change in the structure of the flame and hence changes the duration of combustion. It is suggested that flame temperature reduction is the most important factor influencing NO formation [2, 3].

Experiments were carried out [7] using the setup to prove the efficacy of EGR as a technique for NO_x reduction. It is seen that the exhaust gas temperatures reduce drastically by employing EGR. This indirectly shows the potential for reduction of NO_x emission. This can be concluded from the fact that the most important reason for the formation of NO_x in the combustion chamber is the high temperature of about 2000⁰ K at the site of combustion. Thermal efficiency and brake specific fuel consumption are not affected significantly by EGR. However particulate matter emission in the exhaust increases, as evident from smoke opacity

observations. Diesel engines score higher than that of other engines in most aspects like fuel consumption and low CO emissions, but lose in NO_x emissions. EGR is proved to be one of the most efficient methods of NO_x reduction in diesel engines. The increase in particulate matter emissions due to EGR can be taken care by employing particulate traps.

By increasing the EGR ratios, the heat release rates during premixed combustion, which is characterized by rapid burning and which significantly governs NO_x formation, can be suppressed more efficiently. Furthermore, the combined effects of EGR and supercharging achieved a considerable improvement in combustion along with a reduction in NO_x. The results show that NO_x can be reduced almost in proportion to the EGR ratio and that an approximately 50% NO_x reduction at a 20% EGR ratio can be achieved without deteriorating smoke and unburned HC emissions [8].

Most of the studies explained above are confined to the diesel EGR application and no oxygenated fuel has been touched upon to correlate the performance of a naturally aspirated diesel engine in an alternative fuel condition. In this paper, cold EGR technique is being used with the implementation of neat biodiesel *i.e.* *Jatropha methyl ester*. Biodiesel itself is known to reduce the exhaust emissions, except NO_x. An attempt is made to assess the NO reduction aspect with EGR. Same test is being conducted with the neat diesel application and EGR for the sake of comparison.

II. EXPERIMENTAL SETUP

Fig. 1 : Schematic arrangement of the engine test bed, Instrumentation and data logging system.

2.1 Direct injection (DI) Diesel Engine

The DI diesel engine often used for on board compressed air applications (make Kirloskar company, Pune) is used for conducting the experimentation. The details of the engine are given below.

Table 1. Specifications of the DI- Diesel Engine

Rated Horse power:	5 hp (3.73 kW)
Rated Speed:	1500rpm
No of Strokes:	4
Mode of Injection and injection pressure	Direct Injection, 200 kg/cm ²
No of Cylinders:	1
Stroke	110 mm
Bore	80 mm
Compression ratio	16.5

2.2 Engine Loading System

Engine is loaded with eddy current dynamometer and a spring balance as shown in [Fig. 2]. The load on the engine can be changed with the dynamometer control panel shown in. Full load on the engine is equal to 40 kg on the spring balance. This dynamometer is popular for its stable and consistent readings even in the case of minor variation in engine speed and engine vibration. To accommodate the crank angle encoder, the dynamometer is fixed in parallel to the engine with a belt drive coupled to the engine as shown in [Fig. 2].

Fig. 2 : Belt coupled Engine and Eddy current dynamometer with electric control panel on the right side.

2.3 Exhaust gas recirculation system

The exhaust gas from the engine is collected into a cylinder which is water cooled and the cold gas is sent into another cylinder in parallel which is connected to the engine inlet. A separate piping with a control valve

from an air tank is connected to the pipe from the second cylinder of the EGR system which leads to the engine inlet. The filtered exhaust gas is also controlled by a valve as shown in Fig. 4.

There are two flow measuring devices with the hotwire anemometer arrangement as shown in Fig. 4. One device is for measuring the neat air coming in from the accumulator and other device is meant to measure the filtered gas from the exhaust cylinder. Based on these two measurements and making use of the definition for the percentage of exhaust gas recirculation, convenient software is designed to instantly calculate the percentage mass wise and display (Fig.3). By controlling the fresh air valve and the exhaust valve, the percentage of EGR can be adjusted to the desired value. A part of the incoming air is replaced with the cold exhaust gas in this experiment.

III. RESULT DISCUSSION

Experimentation is carried out at various engine loads to record the cylinder pressure and finally to compute heat release rates with respect to the crank-angle. Engine performance data is acquired to study the performance along with the engine pollution parameters. The results obtained are discussed at length in the following paragraphs.

3.1 Engine Combustion

The pressure traces have been recorded at all loads and at all percentages of EGR both for the diesel fuel and bio-diesel. In the case of diesel-EGR application (Fig. 5), significant fluctuations in peak pressures are observed in the peak pressure zone which is spread over about 15° to 20° of crank angle. However, the pressure variations in the case of JME-EGR application (Fig. 6) are observed to be quite consistent and smooth over its peak pressure zone understandably because of the better cetane rating of the biofuel. From the pressure curves one can deduce that the delay period is increasing with the increase of EGR rate for both the cases of diesel and JME. This can be assessed from the start of combustion in P- θ (Pressure-Crank Angle) plots in figures 5 & 6. On the implementation of diesel & JME, the peak pressures are falling in consonance with the increase in EGR percentage. The increased ignition delay with the increase in EGR may be held responsible for the reduction of peak pressures. This fall in peak pressures with the increase in EGR percentage may also be attributed to the levels of dilution imparted by the increase in re-circulated exhaust gas.

With the increase of EGR, pronounced diffused combustion is observed in both the cases of diesel and JME which is quite clearly evident from the CHRR curves (Fig.7 & Fig. 8). The after combustion in the case

of diesel fuel is more pronounced at the EGR rate of 14%. One can observe widening gap between CHRR curves after the peak CHRR points in the case of higher EGR rates. Combustion in later stages is more erratic in both the cases of diesel as well as JME which may have lead to higher exhaust temperatures.

Fig. 3 : Diesel Engine Test rig with EGR system

Fig. 4 : Exhaust Gas Recirculation system

'After combustion' is more pronounced in the case of diesel-EGR operation. 400° to 500° of crank angle duration witnessed significantly greater separation of CHRR curves (Fig. 7). There is a progressive increase of CHRR which ensues with the increase of EGR rate. Whereas, the increase in CHRR witnessed in the case of JME-EGR run in the same crank angle duration mentioned above is less significant comparatively. However, the *absolute CHRR* for the neat JME operation is higher than when compared to neat diesel in the same crank duration.

3.2 Engine Performance

It can be observed that in the case of diesel, there is sudden drop in SFC with the application of load for 7% EGR which is evident from Fig.9 (graph drawn between specific fuel consumption (SFC) and Equivalence Ratio which rises in consonance with load) and this percentage is consistent even for the JME and its associated EGR percentages as shown in Fig.10. At full load, minimum SFC of 0.31 kg/kW-hr is observed for JME with 7% EGR and this value is minimum when compared to all other EGR percentages with JME implementation (Fig.10). In the case of diesel application the minimum value of SFC recorded is with 7% EGR at full load running of the engine which is at 0.29 kg/kW-hr (Fig. 9). There is more than 3% decrease in SFC in the case of diesel with 7% EGR when compared to the neat diesel application at the same load and this decrement is about 11% in the case of JME with 7% EGR when compared to neat JME application at the same load.

The effectiveness of 7% EGR can be gauged in the case of brake thermal efficiency versus equivalence ratios. The brake thermal efficiency is 30.2% for JME with 7% EGR and at 0.62 value of Equivalence ratio (Fig. 12). This efficiency is the maximum one when compared to the ones with the other EGR percentages. There is a steep hike of about 11% of brake thermal efficiency when compared to the neat JME operation with no EGR. Excess Oxygen in the re-circulated gas is responsible for sufficient combustion to reduce the specific fuel consumption in the case of bio-diesel at higher loads. This can be acclaimed to increase in thermal efficiency at higher loads and higher EGR rates as observed above. With JME implementation, improvement in thermal efficiency is seen in all the cases with EGR even in the part load conditions like one fourth full load, half full load and three fourth full loads (Fig.12). JME being an oxygenated fuel and the excess Oxygen in the re-circulated gas may be responsible for this improvement.

In the case of diesel at 7% EGR which, incidentally happened to be the case in which the brake thermal efficiency reached its maximum value at full load, the brake thermal efficiency recorded is 28.7% (Fig. 11). This value is lesser than the peak value at full load operation with JME and 7% EGR operation. Obviously there is about 5% increase in thermal efficiency when the bio-diesel is used.

3.3 Engine Emissions

NO and HC emissions are complementary to each other and a visible trade-off is there between them in the case of diesel. At a particular load when NO is decreasing with the increase of EGR, HC is increasing almost commensurating with the degree of decrease (Fig. 13 & 15) and vice versa.

In the case of diesel, NO levels decreased to 849 ppm for 7% EGR at full load when compared to neat diesel application. There is a drop of 685 ppm of NO from neat diesel operation at 7% EGR with diesel. This decrement can be acclaimed to the presence of re-circulated cold exhaust gas which reduces the combustion temperatures. When referred to diesel fuel operation, there is greater amount of 'after combustion' which has increased with the EGR percentage which can be estimated with the cumulative heat release in the diffused combustion stage leading to NO emission increase with the increase of EGR thereafter. Inadequate oxygen availability in this process may have lead to

incomplete combustion, which obviously raises the 'HC' levels (Fig.15).

NO emission is slightly more at full load for the bio-diesel application and at part loads the NO emission is lower in the case of diesel comparatively (Fig.14) with respect to some EGR percentages. Increase of NO emission is observed after 7% EGR and for the EGR of 14% the NO emissions are appreciably higher whereas in the case of bio-diesel with EGR the NO emission decreased and fallen by a maximum value of 240 ppm. This is because of higher cetane rating of the biofuels and early injection of biodiesel due to its higher bulk modulus.

HC emission levels are more for diesel with EGR at all the loads when compared to neat diesel application since the presence of exhaust gas impedes the burning rate. There is an increase in HC emissions from 0% EGR up to 7% EGR and then it fell marginally at 14% EGR at part loads. The oxygen content in the re-circulated exhaust itself is the source for combustion in the case of higher exhaust gas circulations. In the case of JME with exhaust gas circulation (Fig.16), HC emissions decreased first with the increase of EGR (up to 7%) because of molecular oxygen available and then increased for the rest of the higher EGR percentages because of bad flame diffusivity. Oxygenated biofuel reduced HC emission almost by 50% in most of the cases at full load. With the introduction of EGR, there is an increase of HC in both the cases of diesel and JME and maximum increase is by 49ppm and 39ppm respectively at full load. HC emission level is at minimum with 45ppm in the case of JME with 7% EGR at full load.

Emission of CO is more for diesel with EGR than JME with EGR (Fig.17 & Fig.18). Higher levels of CO emissions in the case of diesel may be due to the unavailability of sufficient oxygen for complete combustion. Biodiesel application is a proven application for reduction in tail pipe emissions especially HC, CO, CO₂, and smoke levels. Also, in the case of diesel with increase in EGR implementation, a consistent increase in CO level has been observed at all loads. Incomplete combustion due to the dilution may be attributed to this increase. Similar trend is also observed with neat JME and JME with EGR at all loads but with lesser levels of CO emission when compared to diesel with similar conditions of load and EGR percentages. Inherently available free oxygen in the biofuel may have lead to better combustion in these cases when compared

diesel and diesel with EGR. Among all the EGR cases with both diesel as well as JME at full load, JME with 7% EGR recorded minimum CO emission level which is at 0.14%

Fig. 5 : Pressure signatures at full load for all EGR percentages with neat diesel operation.

Fig. 6 : Pressure signatures at full load for all EGR percentages with neat JME operation

Fig. 7 : Cumulative Heat release rate curves at full load for Diesel operation with different EGR percentages.

Fig. 8: Cumulative Heat release rate curves at full load for JME operation with different EGR percentages

Fig. 11: Brake Thermal efficiency Thermal Efficiency versus Equivalence ratio for diesel operation

Fig. 12: Brake Equivalence ratio for JME operation

Fig. 13: Nitric Oxide versus Brake Power for diesel run

Fig. 14: Nitric Oxide versus Brake Power for JME run

Fig. 9: Brake Thermal Efficiency versus Equivalence ratio for diesel operation

Fig. 10: Specific fuel consumption versus Equivalence ratio for JME operation

Fig. 15

Fig. 16 : HC versus Brake Power for JME run Power for JME run

Fig.17 : CO versus brake power for diesel run power for diesel run

Fig.18: CO versus brake power for JME run

IV. CONCLUSION

Diesel fuel in the conventional diesel engine is replaced totally with Jatropha methyl ester and various trials were made with different EGR ratios. Combustion, performance, emissions parameters are measured and compared with that of Diesel. From the above results and discussion the following conclusions are drawn.

1. Sustained peak pressures are observed in the case of JME- EGR operation for considerable duration of crank angle. Conversely, in the case of diesel- EGR application after attaining peak pressure, there is subsequent attenuation observed.
2. Delayed combustion is observed both in the cases of Diesel and JME with EGR application. Delayed combustion is increasing with respect to the EGR percentage. This *after-combustion* is responsible for the rise in exhaust gas temperatures.
3. Peak pressures have reduced with EGR percentage increase in both the cases with EGR implementation.
4. 7% EGR is the most beneficial one which is true in both the cases of Diesel and JME in all respects.
5. General 'NO' reduction is observed with EGR.
6. Emission of CO is more for Diesel with EGR than JME with EGR.

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