Critical Review of Effect of EGR on CI Engine Running on Biodiesel and Its Blends

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Abstract— Increase in energy demand, emission norms and depletion of oil resources have caused the researchers to find alternative fuels for internal combustion engines. Biodiesel is an alternative which is derived from vegetable oils or animal fats through transesterification process. Diesel engines have fuel economy and durability advantages for large heavy-duty trucks, buses and passenger cars. Use of biodiesel gives higher NO_x emission from compression ignition (CI) engine. Exhaust gas recirculation (EGR) is an effective method to reduce NO_x from CI engine. The favorable conditions for formation of NO_x are higher flame temperature and high oxygen availability which is affected using EGR. The objective of this paper is to review the effect of EGR on CI engine running on biodiesel and its blends.

Index Terms—Biodiesel, EGR, Emission, NO_x

Nomenclature

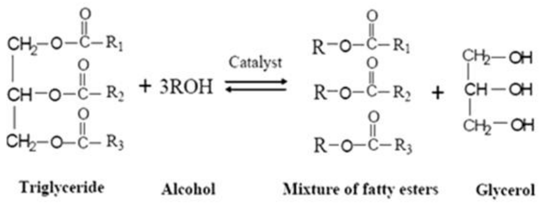
BTE	:	Brake Thermal Efficiency
BSFC	:	Brake Specific Fuel Consumption
EGT	:	Exhaust Gas Temperature
CI	:	Compression Ignition
NO_x	:	Oxides of Nitrogen
CO	:	Carbon Monoxide
HC	:	Hydrocarbon
EGR	:	Exhaust Gas Recirculation
B20	:	20 % Biodiesel
HP	:	High Pressure
LP	:	Low Pressure
HACA	:	hydrogen abstraction C_2H_2 addition
PAHs	:	polycyclic aromatic hydrocarbons
VGT	:	variable geometry turbocharger

I. INTRODUCTION

There is continuous depletion of fossil fuels. Environmental pollution is becoming a serious problem. All these have caused researchers to focus their interest on the study of alternative fuels for Internal Combustion engines. The alternative fuels are alcohols, biodiesel, natural gas, etc. Fuels derived from renewable biological resources for use in diesel engines are known as biodiesel. Biodiesel is environment friendly fuel similar to petrol-diesel in combustion properties. Diesel engines known as compression ignition (C.I.) engines are widely used as power source. Diesel engine is better power source due to higher efficiency, performance and fuel economy than spark ignition (S.I.) engine. Exhaust from compression ignition (C.I.) engine, is a mixture of many undesirable constituents known as pollutants. The use of biodiesel in diesel engine does not require any engine modification. Many researchers have found that biodiesel fueled engine produce higher NO_x emission compared to diesel. EGR is an effective technique of reducing NO_x emission from the diesel engine.

A. Transesterification

Vegetable oil is considered as feedstock for the biodiesel production and the method of biodiesel production is known as transesterification [1]. The transesterification reaction is given below in equation (1).



(1)

Transesterification is a chemical process of transforming large, triglyceride molecules of vegetable oils and fats into smaller molecules, similar in size to the molecules of the species present in diesel fuel [1].

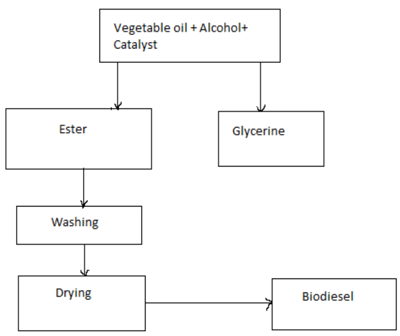


Fig.1 Biodiesel Production

B. Fuel Properties

Biodiesel is a plant derived, not petroleum derived. It can be domestically produced. Biodiesel production reduces petroleum imports. It is biodegradable. Compared to conventional diesel fuel, its combustion products have lower carbon monoxide, sulfur oxides particulates, hydrocarbons etc. Vegetable derived biodiesel properties follow close to that of diesel. The properties of fuels are shown in following table.

Table 1 Fuel Properties [5, 7, 8, 11**]**

Properties	Diesel	Waste cooking oil	Rice-bran oil	Karanja oil	Undi oil
Density at 15°C (gm/cc)	0.835	0.89	0.8908	0.856	0.8653
Kinematic viscosity at 40°C (cst)	1.90	2.72	6.46	4.52	1.744
Flash Point (°C)	44	186	150	187	188
Calorific Value (MJ/Kg)	42.21	35.401	10.402	36.11	39.21

C. Exhaust Gas Recirculation (EGR)

EGR is an effective technique for reducing NOx formation in the combustion chamber of C.I. engines. Fig.2 shows the arrangement of exhaust gas recirculation (EGR) system. In EGR technique, about 10% to 30% of the exhaust gases are recirculated back into the inlet manifold where it mixes with the fresh air. This reduces the quantity of O_2 available for combustion. This reduces the O_2 concentration and dilutes the intake charge, and reduces the peak combustion temperature inside the combustion chamber which will reduce the NO_x formation. EGR rate is given by

$$\text{EGR} = \frac{\text{Mass of Air admitted without EGR} - \text{Mass of Air admitted with EGR}}{\text{Mass of Air admitted without EGR}} \qquad (2)$$

D. Mechanism of NO_x formation

NO is formed inside the combustion chamber in post-flame

Combustion process in the high temperature region. NO formation is oxidation of nitrogen present in atmospheric air. The principal reactions at near stoichiometric fuel–air mixture governing the formation of NO from molecular nitrogen are [4]:

$O + N_2 \rightarrow NO + N$
$N + O_2 \rightarrow NO + O$
$N + OH \rightarrow NO + H$

NO is converted to NO_2 by various means such as,

$NO + H_2O \rightarrow NO_2 + H_2$
$NO + O_2 \rightarrow NO_2 + O$

II. GENERAL EXPERIMENTAL SETUP

Experimental setup of diesel engine with EGR is as follows,

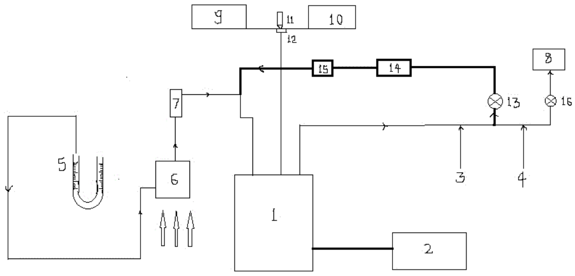


Fig.2 The layout diagram of the engine with EGR system [2]

Engine components are named in following table.

Table 2 Engine Components [2]

1. Engine	7. Air filter	13. EGR control valve
2. Dynamometer	8. Muffler	14. Exhaust gas particulate valve
3. Exhaust gas pipe	9. Diesel fuel tank	15. Orifice meter
4. Exhaust gas analyzer	10. Biodiesel fuel tank	16. Valve
5. U-tube manometer	11. Burette	
6. Air box	12.Controlling valve of fuel	

A diesel engine coupled with a dynamometer is shown in fig.2. From the head difference in the manometer, air flow rate is calculated. The fuel consumption of an engine is measured by determining the time required for consumption of a given volume of fuel. The mass flow rate of fuel consumption is determined by the multiplication of volumetric fuel consumption and density. In the present set up, volumetric fuel consumption is measured by using a glass burette and stop watch. Engine exhaust emissions of HC, CO, CO_2, O_2 and NO_x during experimentation are measured by Multi gas analyzer. The reading of CO is measured in % by volume where as NO_x and HC are measured in ppm using gas analyzer.

In engine performance analysis graphs of BTE Vs load, BSFC Vs load are plotted for diesel fuel and biodiesel blends for various EGR rates. In engine emission analysis graphs of CO Vs load, HC Vs load, NO_x Vs load are plotted for diesel fuel and various biodiesel blends for different EGR rates.

III. RESULTS & DISCUSSION

K. Rajan , K. R. Senthilkumar [1] have studied the Effect of Exhaust Gas Recirculation (EGR) on the Performance and Emission Characteristics of Diesel Engine with Sunflower Oil Methyl Ester. Compared with conventional diesel fuel, they found that the exhaust NO_x reduced about 25% at 20 % biodiesel blends with 15% EGR due to less oxygen available in the recirculated exhaust gases and it lowers the flame temperature in the combustion chamber.

B. Pattanayak et al. [2] analyzed CI engine performance and emission using Karanja oil methyl ester with exhaust gas recirculation process. B20 of Karanja biodiesel shows the best performance characteristic in case of the blended fuels. With increase in percentage of blending the performance characteristic deteriorates as calorific value of biodiesel is less than diesel fuel. The use of biodiesel and its blends reduces CO and HC and increases the NOx emission. Using EGR technique BSFC goes on increasing and BTE of the engine decreases.

P. V. Walke et al.[3] have experimentally studied the Impact of Exhaust Gas Recirculation on the performances of diesel Engine. They found that Brake thermal efficiency decreases with increasing EGR rates. However, this decrease is marginal. The concentration of smoke density goes on increasing and BSFC increases marginally with increase in EGR rates at high load. The exhaust gas recirculation (EGR) has shown definite impact on NO_x reduction.

J. Hussain et al. [4] have studied the Effect of Exhaust Gas Recirculation (EGR) on performance and emission characteristics of a three cylinder direct Injection Compression ignition Engine. It is seen that thermal efficiency is slightly increased and BSFC is decreased at lower loads with EGR compared to that without EGR. At higher loads, increased rate of EGR reduces NO_x to a great extent but disturbs engine performance and emissions. They concluded that higher rate of EGR can be applied at lower loads. It is noted that that 15% EGR rate is found effective to reduce NO_x emission substantially without deteriorating engine performance in terms of thermal efficiency, BSFC, and emissions.

N. Dagar and I. H. Shah [5] investigated Two cylinder diesel engine using biodiesel and diesel as fuel with EGR technique. They found that the exhaust gas temperature of engine with diesel as fuel to be lower than biodiesel and its blends with constant EGR rate. The brake thermal efficiency and specific fuel consumption of diesel engine with biodiesel and its blends were found to be higher than diesel as fuel with 15% EGR rate.

K. Ashok et al. [6] studied the Combustion Characteristics and Performance of a direct injection diesel engine fueled with Rice-Bran oil derived biodiesel/diesel blends. They concluded that fuel properties of rice-bran biodiesel were within limits except calorific value. The BSFC showed increasing trend and BTE decreased with increase in the proportion of biodiesel in the blends. The amount of CO and HC in exhaust emission reduced, whereas NO_x increased with increase in percentage of rice-bran biodiesel in the blends. It is seen that Rice-bran biodiesel may be safely blended with diesel up to 20% without significantly affecting the engine performance.

R. Bawane et al. [7] tested CI engine performance fueled with Undi Oil Biodiesel under variation in blend proportion, compression ratio & engine load. BTE is decreased and BSFC are higher for biodiesel and its blends than that of diesel. The HC emission gives decreasing trend with increase in compression ratio for the entire range of fuels. The NO_x emission for entire range of fuel is higher at low compression ratio.

M. Kassaby et al. [8] studied the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel. Biodiesel can be blended up to 20% at any compression ratio with safety consideration. BSFC increases and BTE decreases as biodiesel increases. It is seen that BSFC decreases and BTE increases as compression increases. CO_2 and NO_x increased with compression ratio. Increase in the compression ratio improved the performance and cylinder pressure of the engine and it has shown more benefits with biodiesel than that of diesel.

Y. Park and C. Bae [9] have experimentally investigated the effects of high/low pressure EGR proportion in a passenger car diesel engine. It is found that the intake manifold temperature showed decreasing trend as the LP EGR portion increased because the LP EGR was cooled down more than the HP EGR due to longer supply line. The VGT nozzle opened more widely to maintain the boost pressure, which resulted into the lower BSFC. The pumping loss showed a decreasing order with the increase of the LP EGR portion. NO_x emissions showed good improvement when increasing the LP EGR.

W. Zhang et al. [10] studied the influence of EGR and oxygen-enriched air on diesel engine NO–Smoke emission and combustion characteristic. The authors have noted that proper combination of EGR rate and oxygen concentration can achieve low NO–Smoke emission. Smoke opacity decreases effectively in case of oxygen-enriched combustion of diesel engines. The numerical simulation results indicate that oxygen enriched combustion suppress HACA reactions and is reducing the formation of large molecule PAHs.

K. Muralidharan and D. Vasudevan et al. [11] evaluated Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. Compared with the conventional standard diesel at compression ratio 21,It has been found that the performance of the B40 blend is better. At lower and medium percentages, waste cooking oil methyl ester is hopeful substitute for diesel fuel.

W.Adaileh et al. [12] studied performance of diesel engine fuelled by a biodiesel extracted from waste cocking oil. Waste vegetable oil has been found to be safe and efficient alternative fuel. It has a low impact on the environment. A B20 blend produced marginal reductions in the CO, HC, and smoke emissions when compared with standard diesel and B5.

D. Agarwal et al. [13] evaluated the Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine. With EGR, Exhaust gas temperature goes on decreasing. Thermal efficiency has shown slight increase and BSFC decreased at lower loads with EGR when compared to that of without EGR. BSFC and thermal efficiency are almost similar with EGR than that without EGR at higher load. Hydrocarbons, opacity, carbon monoxide have increased with EGR, but giving good reduction in NO_x emission. It is observed that 15% EGR rate is well suited to reduce NO_x emission. Higher soot gets deposited on cylinder head, injector tip, and piston crown of engine when EGR is used.

Avinash Kumar Agarwal and Atul Dhar [14] experimentally investigated performance, emission and combustion characteristics of Karanja oil blends fuelled DICI engine. Thermal efficiency of engine using Karanja blends is less than that of mineral diesel. Calorific value of Karanja oil is lower than that of mineral diesel. Therefore BSFC increases with increasing proportion of Karanja oil in the blends. Engine using K10 blend only shows thermal efficiency close to that of pure diesel at lower load. Karanja oil gives CO_2 emissions higher than that of mineral diesel. Smoke opacity of K100 has been found more than mineral diesel at lower engine loads. Smoke opacity is less than mineral diesel for lower karanja blend and lowest for K20. Lower percentage blends (up to 20% v/v) can be safely used as alternate fuels to pure diesel.

Achuthanunni V and Baiju B [15] have experimentally investigated a Diesel-Biodiesel fuelled compression ignition engine with Exhaust Gas Recirculation (EGR). Biodiesel is an oxygenated fuel and it gives higher NO_x emissions. 10% exhaust gas recirculation is effective to reduce NO_x emission. The oxygen concentration in the combustion chamber is decreased and flame temperature also reduces because of EGR use in engine. At all loads, brake thermal efficiency of biodiesel is close to that of diesel. When compared to other blends, B20 has better performance. Authors have carried out experiment on single cylinder diesel engine with diesel and biodiesel blend using 10% EGR. It showed minimized pollution and improved performance. 40% NO_x reduction has been observed by using 10% EGR.

P. Saichaitanya et al. [16] have studied impact of cold and hot Exhaust Gas Recirculation (EGR) on diesel engine. From the experiment, authors have found that cold EGR with 15% exhaust gas recirculation is giving optimum engine performance along with reduction in emissions.

P. Srinivasa Rao et al. [17] did evaluation on performance and emission characteristics of diesel engine fuelled by biodiesel derived from linseed oil. There is no engine seizing, injector blocking during the whole operation of engine running with different blends of linseed oil and diesel. They concluded that the blend L30 gives better performance considering brake thermal efficiency, specific fuel consumption and emission parameters.

A. Engine Performance Analysis

1. Brake Thermal Efficiency (BTE)

Thermal efficiency is showing slight increase with EGR at lower engine loads. The reason for this is re-burning of hydrocarbons entering the combustion chamber with the recirculation of exhaust gas. Exhaust gas has less CO_2 and high amount of O_2 at part load. Partly cooled EGR is like a pre-heater of the intake mixture.

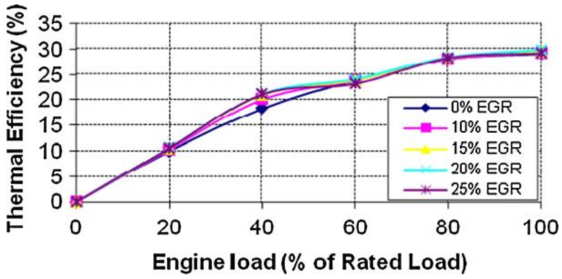


Fig.3 Thermal Efficiency for Different EGR Rate [4]

2. Brake Specific Fuel Consumption (BSFC)

Fig.4 represents comparison of BSFC for different EGR rates. BSFC is lower at lower loads for engine operated with EGR compared to without EGR. It shows behavior of brake specific fuel consumption with torque at different EGR rates. There is marginal increases in BSFC observed with increasing EGR at different torque.

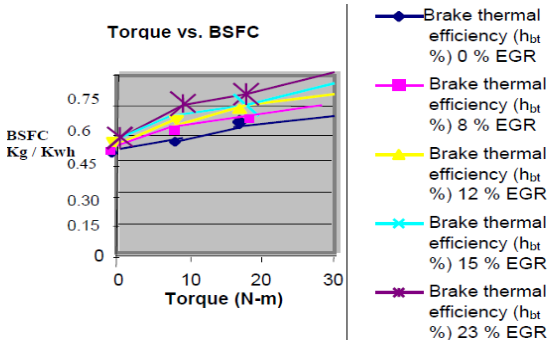


Fig.4 BSFC Vs Torque at different EGR rates [3]

3. Exhaust Gas Temperature (EGT)

Fig. 5 shows variation of the exhaust gas temperatures. It indicates that with increase in load, exhaust gas temperature also increases. For engine operated with partly cooled EGR, exhaust gas temperature is generally lower than exhaust gas temperature at normal operating condition. Exhaust gas temperature has decreasing trend with increase in EGR rate. Insufficient oxygen for combustion and high specific heat of intake air yields temperature reduction for engine operating with EGR.

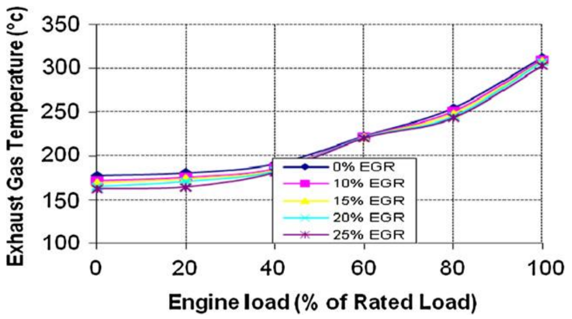


Fig.5 Exhaust Gas Temperature for various EGR rates [4]

B. Engine Emission Analysis

1. Unburned Hydrocarbon (HC) and Carbon monoxide (CO)

From the graphs it is clear that HC and CO emissions increase with increase of EGR. Rich air-fuel mixtures results at different locations inside the combustion chamber because of insufficient availability of oxygen using EGR. The heterogeneous mixture is formed which undergoes incomplete combustion and gives higher hydrocarbons, and carbon monoxide emissions.

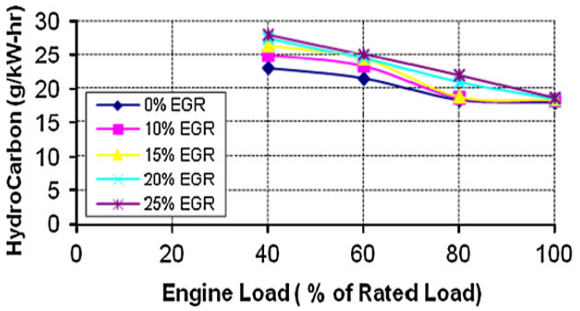


Fig.6 Hydrocarbons for different EGR rates [4]

Due to insufficient oxygen for EGR operation, heterogeneous mixture is formed which undergoes incomplete combustion and gives higher carbon monoxide as shown in fig.7.

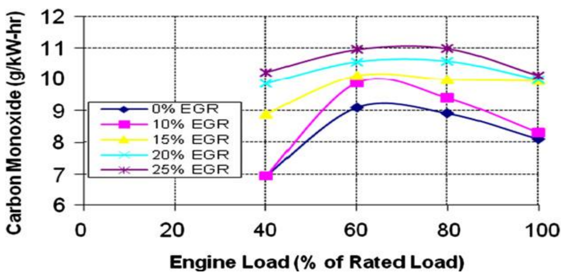


Fig.7 Carbon monoxide for different EGR rates [4]

2. Oxides of Nitrogen

Figure 8 gives the variations of NOx emissions of diesel and sunflower methyl ester with and without EGR. Reduced oxygen quantity and lowered flame temperatures in the combustion chamber lead to reduction in NOx emissions using EGR in diesel engines. In case of biodiesel blends without EGR, NOx emissions are higher than that of diesel. The reduction in NO_x is higher at higher loads.

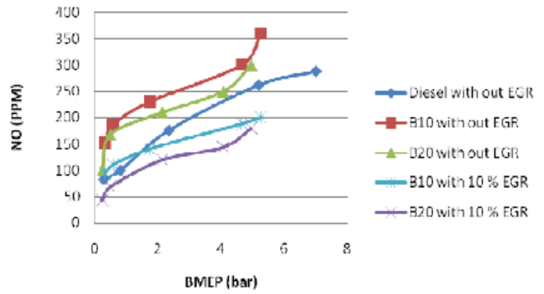


Fig.8 NOx Emission Vs BMEP for different EGR rates [15]

3. Smoke Opacity

With increase in the EGR rates, the smoke increases. The effect of cold and hot EGR is insignificant in case of smoke opacity. The smoke opacity level variation is higher at higher load than that at lower loads. Because of insufficient oxygen in EGR operated engine case, there is relatively incomplete combustion which gives formation of particulate matter.

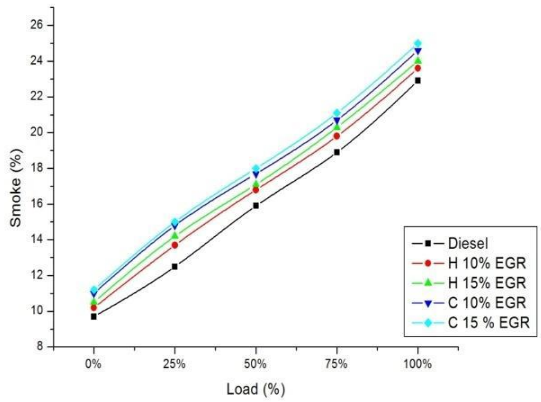


Fig.9 Variation of smoke with load for different percentages of cold and hot EGR [16]

C. Effect of high/low Pressure EGR

1. Intake manifold Temperature

As LP EGR portion is increased, the intake manifold temperature decreases gradually .This leads to the increase of volumetric efficiency. The LP EGR gas is passed through LP EGR cooler and an intercooler and then it is introduced to the intake manifold. The HP EGR gas is cooled once only in a HP EGR cooler.

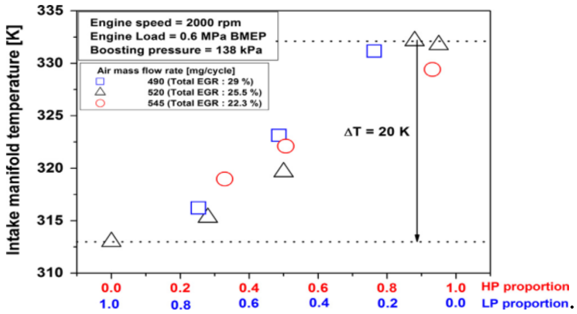


Fig.10 Intake manifold temperature Vs HP/LP EGR proportion [9]

2. Required cooling power of intercooler

From the fig.11 it is understood that with the increase of the LP EGR portion, the required cooling power for the intercooler increases steadily for three mass flow rates of fresh air because the LP EGR gas is induced upstream of the compressor. The intercooler design with the LP EGR should be considered as an essential factor when managing the diesel engines intake system.

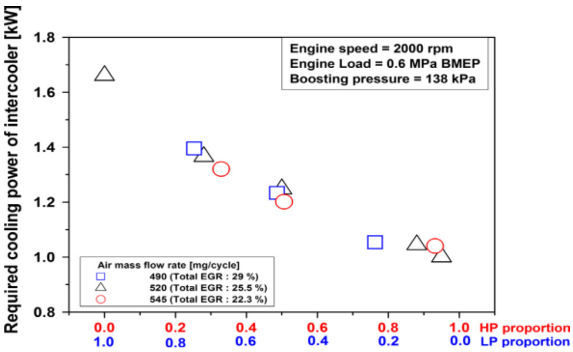


Fig.11 Required cooling power of intercooler with the variation of HP/LP EGR Proportion [9]

3. BSFC Vs HP/LP EGR

In fig.12 the brake specific fuel consumption (BSFC) shows decreasing trend with the increase of the LP EGR portion. The exhaust manifold pressure lowers as the LP EGR portion increased. This is because VGT nozzle opened more widely with the increase of LP EGR portion to maintain a constant boost pressure resulting in a lower exhaust manifold pressure; in other words, a lower pumping loss. Thus, the BSFC reduces with the increase of LP EGR portion.

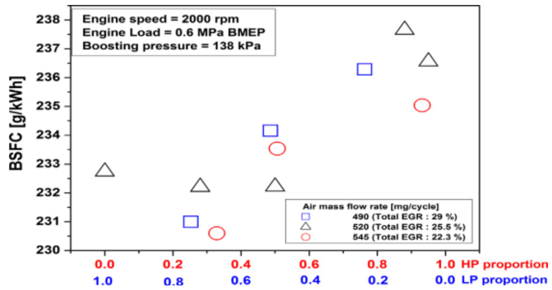


Fig. 12 BSFC characteristics with the variation of HP/LP EGR proportion [9]

D. EGR and Oxygen enriched air effect on NO-smoke emission

Fig.13 and fig.14 show variation of smoke and NO for different EGR rates respectively. From fig.13, as EGR rate increases, smoke number also increases. But with increasing oxygen, smoke decreases which helps in complete combustion.

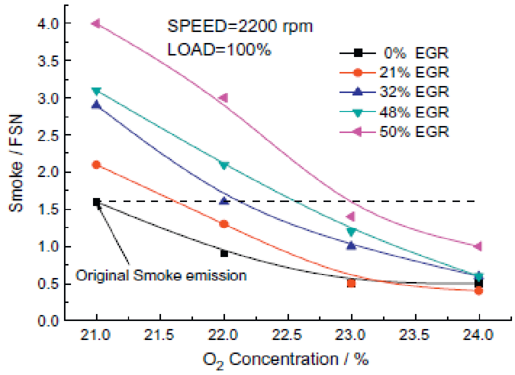


Fig.13 Influence of O_2 concentration and EGR rate on smoke emission [10]

From fig.14, it is seen that NO_x emission decreases with increasing EGR rate but NO_x increases with increase in O_2 concentration.

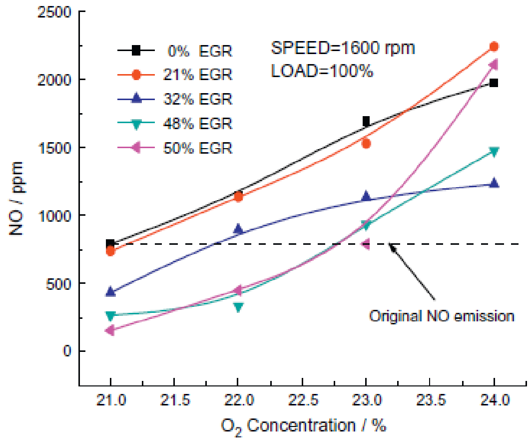


Fig.14 Influence of O_2 concentration and EGR rate on NO emission [10]

The proper combination of EGR rate and oxygen concentration gives low NO_x and low smoke as well without significant power loss as shown in fig.15 below.

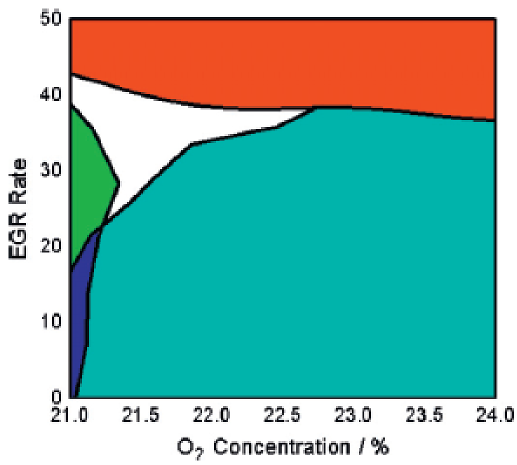


Fig.15 EGR Vs O_2 with NO-smoke emission. (1) Red Zone: Power Loss zone, (2) Green Zone: High Smoke Emission Zone, (3) Blue Zone: High Smoke and NO

Emission Zone, (4) White Zone: Low Smoke and NO Emission Zone [10]

IV. CONCLUSION

To use vegetable oils in diesel engine, transesterification process is carried out to reduce viscosity and density of oil. Biodiesel derived from vegetable oils can be blended with diesel and safely used in diesel engine without modification in engine. Use of biodiesel in compression ignition engine gives higher NO_x emission and lowers HC, CO emissions. EGR is an effective method to reduce oxides of nitrogen emission from engine. Higher rate of EGR reduces NO_x to great extent but deteriorates engine performance in terms of thermal efficiency, specific fuel consumption. Lower percentage of biodiesel blend and lower EGR rate can be safely used in diesel engine without deteriorating engine performance. It has been studied that compression ignition engine running on biodiesel blend along with EGR gives satisfactory engine performance and better engine emissions.

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