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Comparison of Measured and Predicted Performance and the Emission Characteristics of Single Cylinder CI Engine using Pongamia Pinnata based Bio-Diesel

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***Abstract*—** *Diesel being the main transport fuel, developing countries like India spends a lot of money to import petroleum and the use of petroleum based fuels increased in the recent years is the main contributor to the urban air pollution. Finding a suitable alternative to diesel is an urgent need. Biofuels are renewable, can supplement petroleum based fuels. Due to pressure on edible oils, non-edible oils of Pongamia Pinnata (karanja) and Jatropa Curcas are evaluated as diesel fuel extender. Pongamia pinnata based bio-diesel (PBD) is receiving increasing attention in India because of its potential to increase the rural employment and relatively low impact on environment. Diesel engines running on PBD are found to emit higher oxides of nitrogen. In this work a single cylinder constant speed water cooled four stroke direct injection diesel engine is selected for the experimental investigations to model the performance and emission characteristics fueled with plain Diesel and Pongamia Bio-diesel blends PBD10 (10% Pongamia Bio-diesel and 90% Diesel) and PBD20 (20% Pongamia Bio-diesel and 80% Diesel) with different cooled EGR rates (0%, 5%, 10%, 15% and 20%). The performance parameters are analyzed include specific fuel consumption and brake thermal efficiency whereas exhaust emissions include nitric oxide (NO), carbon monoxide (CO) and smoke opacity. The results of the experiments in each case were used to model the performance and emission parameters. Multivariate non linear regression analysis is carried out in Minitab software to model the performance and emission parameters. The predicted values were compared with experimental data.*

Keywords*— *Bio-diesel, EGR, Pongamia Pinnata, Engine modeling, Multiple nonlinear Regression.

I. INTRODUCTION

Share of diesel engine is consistently rising in vehicle market worldwide. New technologies and improvements made the diesel engine more fuel efficient. The main advantage of the diesel engine compared to spark ignition engine is its fuel economy. Extensive usage of automobiles has some demerits and one of them is its negative effect on environment.

Diesel exhaust is produced when an engine burns diesel fuel. It is a complex mixture of many of gases including carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_X), hydrocarbons (HC), sulphur dioxide (SO_2), soot particles, etc,. Hence, stringent emission norms are continuously being imposed on diesel engines. To meet the future emission norms suitable measures need to be taken [1-3]. Bio-fuels have the potential to meet the rapidly growing energy demand in sustainable way. Bio diesels have almost similar energy density, cetane number, heat of vaporization and stoichiometric air fuel ratio compared to plain diesel [4-5]. Using bio-diesel in diesel engine has reduced emissions of CO_2, CO and HC. Most bio-diesels in diesel engine will increase the NO_X emission. But pongamia pinnata based bio-diesel has also reduced NO_X emission. NO_X emission can be further reduced by various techniques like EGR, SCR, etc.

Pongamia pinnata is a non-edible species capable of growing in almost all types of land. The annual production potential is about 9,000 kg per hectare. In India the estimated oil from seeds is about 50,000 tones. The yield from a single tree would be around 25 to 90 kg of seed containing around 27 to 50% of oil. The characteristics of these oils fall within a fairly narrow band and are quite close to those of diesel [4-5].

Raw pongamia oil has less calorific value compared to diesel. This is due to the oxygen content in their molecules. Previous research works show that using straight vegetable oil (SVO) in diesel engines leading to problems in pumping, atomization and gumming, injector fouling, piston and ring sticking and contamination of lubricating oils in the long run operation due to its high viscosity, density, iodine value and poor non volatility [5]. Hence it is essential to reduce the viscosity of the pongamia by methods like preheating, thermal cracking and transesterification etc. Transesterification is the best way to convert the vegetable oils to suit for the use in diesel engines. So pongamia oil (SVO) is converted into bio-diesel through a transesterification process [6]. The obtained Pongamia bio-diesel has properties close to diesel fuel and is found that it can be in engine without any modification. Pongamia bio-diesel was mixed with diesel in varying proportions 10% and 20% by volume (PBD10 and PBD20) with the help of a stirrer. The blends were stirred continuously to achieve stable property values. Properties of diesel, PBD10 and PBD20 are shown in Table 1.

Table.I: Properties of Fuel

Properties	Diesel	PBD10	PBD20
Density at 30 ºC	0.832	0.836	0.841
Calorific Value (kJ/kg)	44000	42600	41500
Viscosity (cSt at 30 ºC)	3.02	3.5	4.3
Flash Point (ºC)	60	68	75

Diesel engines are more efficient than petrol engines. However, when compared to petrol engine, diesel engines have higher emissions of NO_X and much higher emissions of particulate matter. The recycling of some of the exhaust back into the engine intake system, commonly known as exhaust gas recirculation (EGR) has become almost essential for achieving significant NO_X reductions to meet the current and future diesel emission regulations [E,F,G]. Exhaust Gas Recirculation (EGR) is a simple and most effective way of reducing NO_X emissions from diesel engines [E]. EGR changes the diesel combustion process of engine because of three broadly defined effects [7-9, 11].

Thermal Effect: The recycled inert gases, predominantly carbon dioxide (CO_2) and water vapor (H_2O) increase the specific heat capacity of the intake charge, thereby lowering the temperatures during the compression and combustion processes.

Dilution Effect: The replacement of intake oxygen with the inert gases dilutes the intake charge, results in a reduced excess-air ratio (k), increases the ignition delay and slows down the fuel burning rate due to the deceleration of the mixing between oxygen (O_2) and fuel. Furthermore, the dilution effect contributes to the reduction of the oxygen partial pressure and thus affects the kinetics of the elementary NO formation reactions.

Chemical Effect: The recycled gases also introduce free radicals such as O, H and OH in the cylinder charge, formed by the dissociation of CO_2 and H_2O that are believed to affect the combustion process and NOx formation. In particular, a reduction in the flame temperature is caused by the endothermic dissociation of H_2O.

The EGR (%) is defined as the mass percent of the re-circulated exhaust (M_{EGR}) in the total intake mixture (M_i).

$$\% \text{ EGR} = (M_{EGR} / M_i) * 100$$

However, application of EGR also leads to penalties. In case of diesel engines, these penalties include higher specific fuel consumption and particulate matter emissions. Effectively, a tradeoff between NO_X and soot is observed with the use of EGR [12-15]. The reduction in flame temperature reduces the rate of soot oxidation/re-burning. As a result, in EGR system, more soot is formed during combustion and it remains un-oxidized and eventually appears in the exhaust. The rise in smoke (soot) level of engine exhaust due to EGR affects the engine performance in various ways. Increased soot level causes considerable increase in the carbon deposits and wear of the various vital engine parts such as cylinder liner, piston rings, valve train and bearings.

Regression analysis is a statistical method for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Regression analysis is used for prediction and forecasting [16]. Simple linear regression and multiple linear regression are related statistical methods for modeling the relationship between two or more variables using a linear equation. Simple linear regression refers to a regression on two variables while multiple regression refers to a regression on more than two variables. Linear regression assumes the best estimate of the response is a linear function of some parameters. Sometimes the true relationship is curved, rather than flat. To fit this type of curves, non-linear regression is used.

In this work multivariable non linear regression is carried out using Minitab 16 to predict the engine performance and emission parameter. Gauss-Newton algorithm is used to solve the equations. In this work exponential and power model equations are selected for regression modeling. These non-linear equations can be put into a linear form by appropriate transformations of the either the dependent variable Y or some (or all) of the independent variables X1, X2,…, Xn. This leads to the wide utility of the linear model. Exponential model and power model equations and their linear form are given in equation (1) and equation (2).

Exponential model equation,

$$y = e^{\beta 0 + \beta 1x1 + \beta 2x2 + \beta 3x3 + \ldots} \quad (1)$$

Linear form $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots$

Here, $Y = \ln y$, $X_1 = x_1$, $X_2 = x_2$, $X_3 = x_3$

Power model equation,

$$y = ax^b \quad (2)$$

Linear form: $\ln y = \ln a + b \ln x$ or $Y = \beta_0 + \beta_1 X$

Here, $Y = \ln y$, $X = \ln x$, $\beta_0 = \ln a$, $\beta_1 = b$.

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Here a, b and $\beta_0, \beta_1, \beta_2, ...$ are coefficients, x, X_1, X_2,…are variables.

II. EXPERIMENTAL WORK

The test rig used in this study is kirloskar single cylinder variable compression direct injection four stroke diesel engine. The specifications of the engine are listed in Table 2. The EGR system consists of a piping system taken from the engine exhaust pipe, a heat exchanger to cool the exhaust gases, two control valves (CV1 and CV2) to change the quantity of gases being recycled. The schematic representation of the EGR system shown in Fig.1.

The engine is loaded by an eddy current dynamometer. A computerized data acquisition system is used to collect all engine data and store it in a computer for off line analysis. The data acquisition system collects the following parameters: engine speed, torque, fuel flow rate, air flow rate, and coolant flow rate, temperature of air/coolant/exhaust gas before EGR cooler/exhaust gas after EGR cooler, cylinder pressure data and crank angle degrees. A computer software Engine Test Express V20.25 is used to collect the data and manage the system. The engine was run by using plain diesel and pongamia bio-diesel blends (PBD10 and PBD20) with different EGR rates. For all three fuels readings are taken in 0%, 25%, 50%, 75% and 100% load. The emissions like CO, NO and smoke opacity are measured using Endee portable gas analyzer.

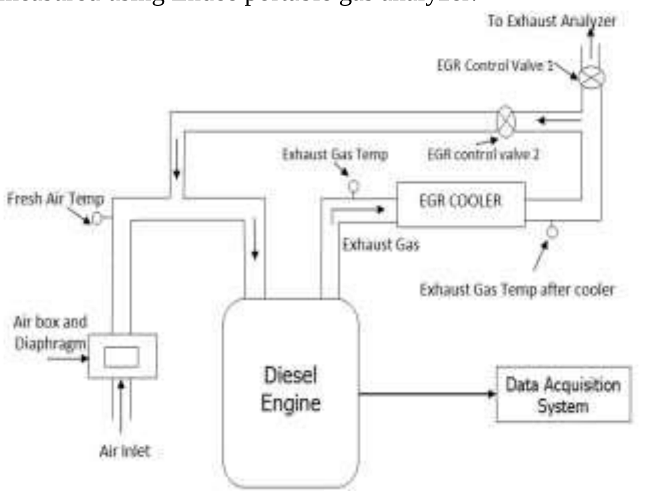

Fig.1: Experimental Setup

Table.II: Specifications of The Engine

Make	Legion brothers, Bangalore,
Type	Kirloskar, single cylinder,
No. of strokes	Four
Bore/stroke	80 mm/110mm
Rated rpm	1500
Injection timing	23 deg btdc
Type of ignition	Compression ignition
Method of loading	Eddy current dynamometer
Method of starting	Manual crank shaft
Method of cooling	Water
Injection pressure	200 bar

III. RESULTS AND DISCUSSION

A. Brake Thermal Efficiency

Fig. 2 shows the comparison of brake thermal efficiency (BTE) for PBD10, PBD20 and diesel (DI) without EGR. BTE is almost comparable for bio-diesel blends and diesel. BTE is slightly increased with EGR at lower engine loads. This is presumably due to the re-burning of hydrocarbons that enter into the combustion chamber with the re-circulated exhaust gas [10, 15]. At higher engine loads, the BTE slightly decreased by EGR. At full load condition % reduction in BTE over an EGR range of 0–20% is 3.8, 3.12 and 3.5 for diesel, PBD10 and PBD20 respectively. The drop in BTE at 20% EGR level is possibly due to predominant dilution effect of EGR leaving more exhaust gases in combustion chamber. The non linear regression equation to predict the BTE in terms of load (W), EGR %, fuel density (FD) and heating value (CV) of fuel is given in equation (3).

$$\ln(BTE) = -1.4 + 0.507 \ln(W) + 0.00065 \ln(EGR) + 0.36 \ln(CV) - 0.13 \ln(FD) \quad (3)$$

BTE of an engine depends on the speed, load, heating value of the fuel and EGR rate. The regression coefficient (R^2), adjusted regression coefficient (R^2 adj.) and standard error of estimate (SEE) for predicting equations are given in Table 3. In the above equation the load and heating value of fuel having larger influence on predicted BTE of the engine. EGR rate have very less influence on BTE. Fig. 2 and Fig. 3 indicates the measured and predicted BTE of diesel (DI M-Diesel Measured and DI P-Diesel Predicted), PBD10 (PBD10 M-PBD10 measured and PBD10 P-PBD10 predicted) and PBD20 (PBD20 M-PBD20 measured and PBD20 P-PBD20 predicted) with 15% EGR. At lower loads predicted and measured BTE are comparable. At full load condition predicted BTE shows 10.5 % of average deviation from the measured BTE.

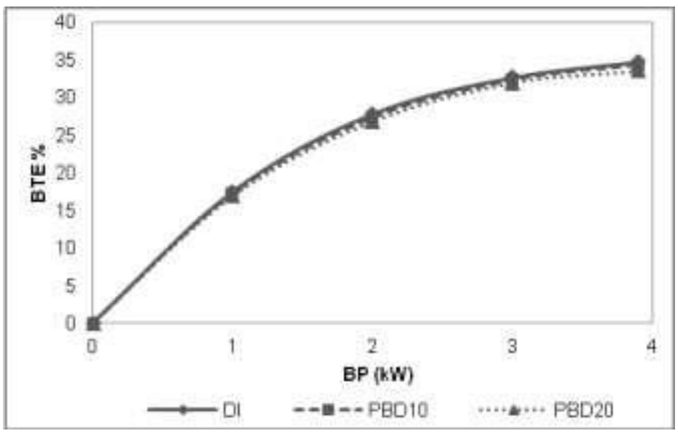

Fig. 2: Comparison of brake thermal efficiency (0% EGR)

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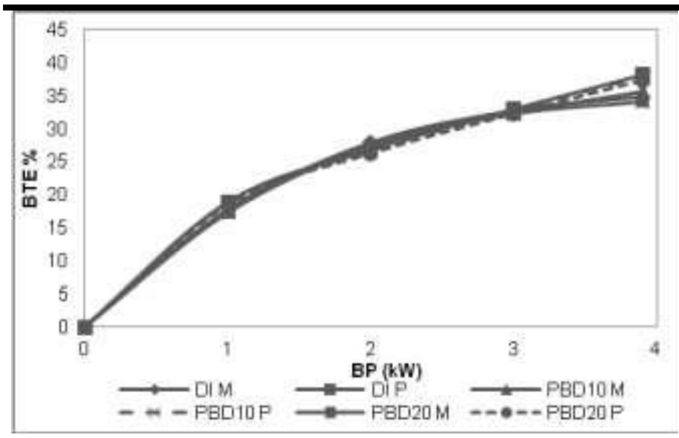

Fig.3: Comparison of Measured and Predicted BTE with 15% EGR

Table.III: Statistical Results of Predicting Equations

Parameter	R^2	R^2 Adj.	SEE
BTE	95.3	94.9	0.06139
BSFC	93.9	93.4	0.06672
NO	96.8	96.6	0.10579
CO	89.3	88.7	0.13199
Smoke	95	94.7	0.15431

B. Brake Specific Fuel Consumption

Fig. 4 demonstrates the variation of brake specific fuel consumption (BSFC) with brake power for diesel, PBD10 and PBD20. BSFC is found to be decreased with increase in brake power. This is due to higher percentage increase in brake power with load as compared to increase in the fuel consumption. BSFC of bio-diesel blends are slightly higher for all experimental range of EGR compared to corresponding BSFC of diesel fuel [10, 15]. This is presumably due to lower calorific value, higher boiling point and viscosity. PBD20 when used with the 20% EGR shows an average increase of 3.8% in BSFC compared to without EGR and 5.3% compared to neat diesel fuel. This may be due to the penalty of exhaust gases containing CO_2 made the combustion difficult. The non linear regression equation to predict the BSFC in terms of load (W), EGR %, fuel density (FD) and heating value (CV) of fuel is given in equation (4).

$$\ln(BSFC) = -18.9 - 0.481\ln(W) + 0.00164\ln(EGR) + 1.85\ln(CV) + 6.68\ln(FD) \quad (4)$$

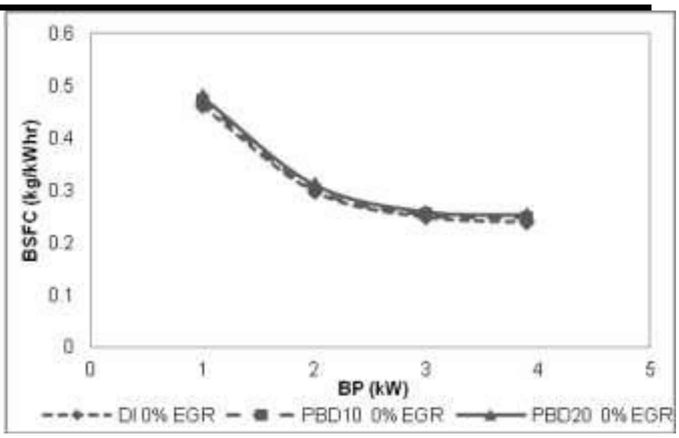

Fig. 4: Comparison of BSFC (0% EGR)

BSFC of an engine depends on the speed, load, heating value of the fuel and EGR rate. Load applied is having more influence on specific fuel consumption. The comparison of measured and predicted BSFC for diesel, PBD10 and PBD20 with 5% and 15% EGR level are shown in Fig. 5 and Fig. 6. At 15% EGR rate predicted BSFC of diesel, PBD10 and PBD20 shows average of 7%, 6.2% and 5.9% variation from the measured BSFC respectively.

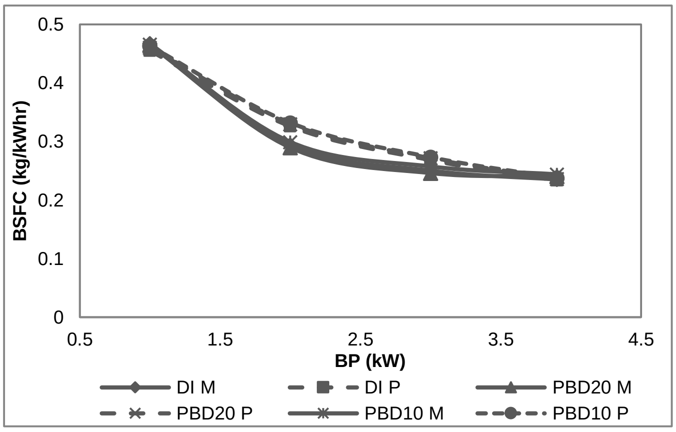

Fig. 5: Measured and Predicted BSFC of Diesel and PBD20 with 5% EGR

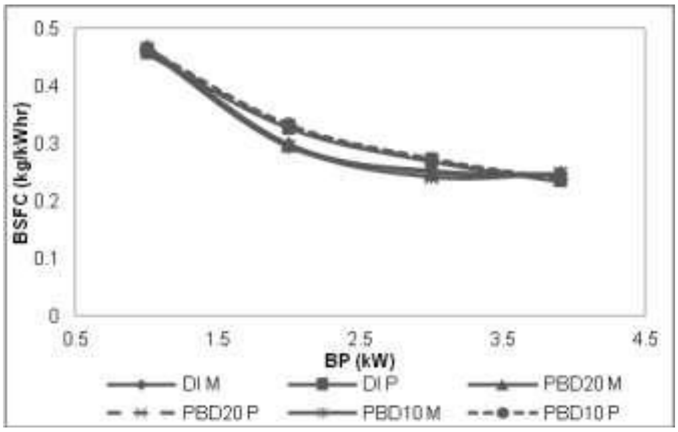

Fig. 6: Measured and Predicted BSFC of Diesel and PBD20 with 15% EGR

C. Nitric Oxide (NO)

Fig. 7 indicates the variation of NO emission with EGR % for diesel, PBD10 and PBD20. NO emission for all fuels

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increases with the increase in brake power. The reason could be the higher average gas temperature, residence time at higher brake power. A greater reduction in the NO emission for both the bio-diesel blends as compared to diesel is noted. NO emission from bio-diesel at all loads, for all EGR rate, is lower compared to diesel under no EGR condition. At full load and 0% EGR condition NO emission level are 66 ppm for diesel, 59 ppm for PBD10 and 42 ppm for PBD20. This is due to the lower heating value of the bio-diesel blends. As EGR level increases NO emission decreases for all three fuels for all the operation range of engine brake power [10, 15, 17, 18]. The reason for the greater reduction in NO with EGR is the reduction of combustion temperature as a result of the addition of exhaust gases to the intake air which increases the amount of combustion accompanying gases mainly CO_2 which reduces the combustion temperature. Even though 20% EGR is able to reduce NO by a large amount, reduction in BTE and large increase in smoke and CO emissions are observed. The NO emission of an engine is determined by peak combustion temperature, pressure and oxygen concentration. The non linear regression equation to predict the NO in terms of load (W), EGR %, fuel density (FD) and heating value (CV) of fuel is given in equation (5).

$$\ln(NO) = -16.1 + (0.126\,W) - (0.0398\,EGR) + (0.000241\,CV) + (10.3\,FD) \quad (5)$$

The comparison of measured and predicted NO emission for diesel, PBD10 and PB20 blends with 0% and 15% are shown in Fig. 8 and Fig. 9.

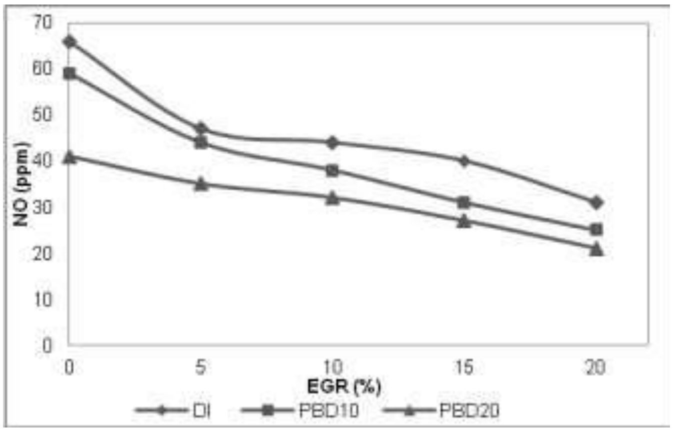

Fig.7: Comparison of NO with EGR

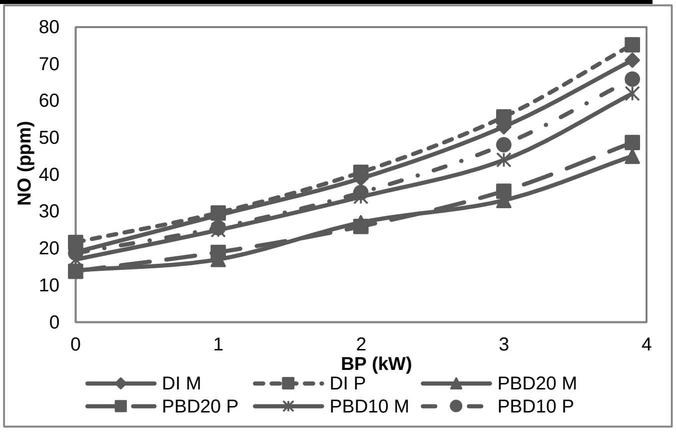

Fig.8: Measured and Predicted NO of Diesel and PBD20 with 0% EGR

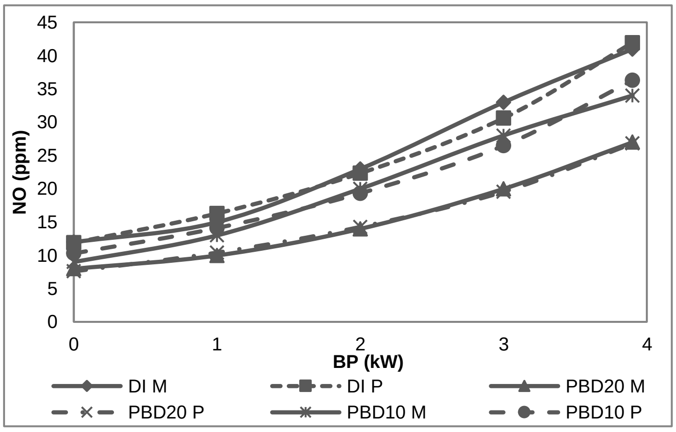

Fig.9: Measured and Predicted NO of Diesel and PBD20 with 15% EGR

D. Carbon Monoxide (CO)

Fig. 10 indicates CO variation with brake power for diesel, PBD10 and PBD20 with 0% EGR. CO emissions are found to be lower for bio-diesel blends compared to diesel with and without EGR. CO levels increases as EGR rate increases for all three fuels [10, 15, 17, 18]. The deficiency of oxygen with the increase in EGR % can be attributed to the rapid growth of CO. However, the excess oxygen content in bio-diesel blends can compensate for the oxygen deficient operation under EGR as a result of which bio-diesel blends maintain a lower CO than diesel at a fixed EGR level. Dissociation of CO_2 to CO at peak loads where high combustion temperatures and comparatively fuel rich operation exists, can also contribute to higher CO emissions. The CO emission of an engine depends on oxygen content and temperature of the combustion chamber. The non linear regression equation for predicting CO emission is given in equation (6).

$$\ln(CO) = 178 + (0.0741\,W) + (0.0318\,EGR) - (0.000949\,CV)\,(166\,FD) \quad (6)$$

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In statistical analysis R^2 value of CO is 89.3% which is not adequate. This is because of the unpredictable trend in CO emission curves. The comparison of measured and predicted CO emission for diesel, PBD10 and PBD20 with 10% and 20% EGR rate are shown in Fig.11 and Fig. 12.

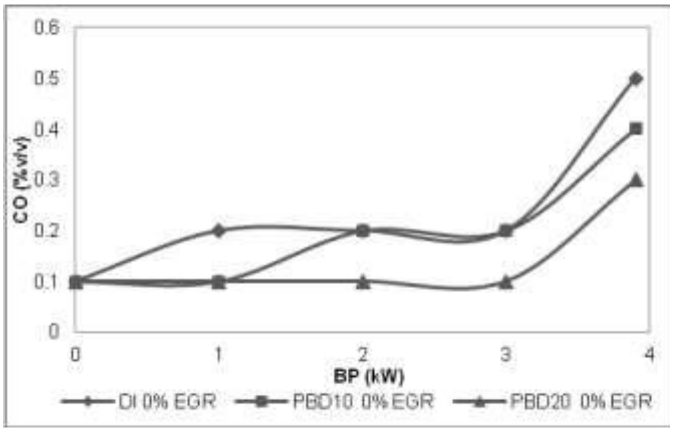

Fig.10: Comparison of CO (0% EGR)

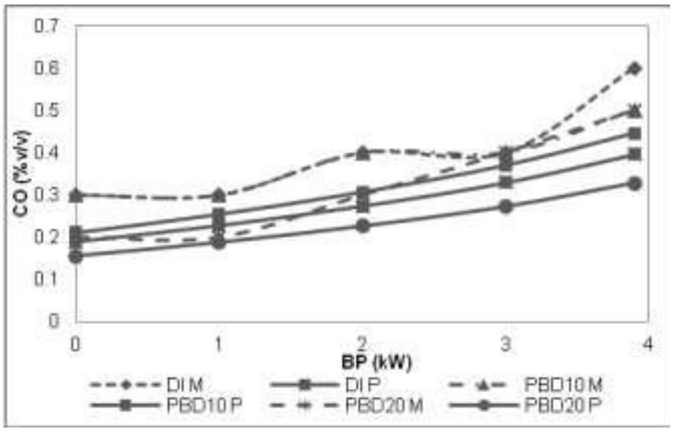

Fig. 11: Measured and Predicted CO of Diesel and PBD20 with 10% EGR

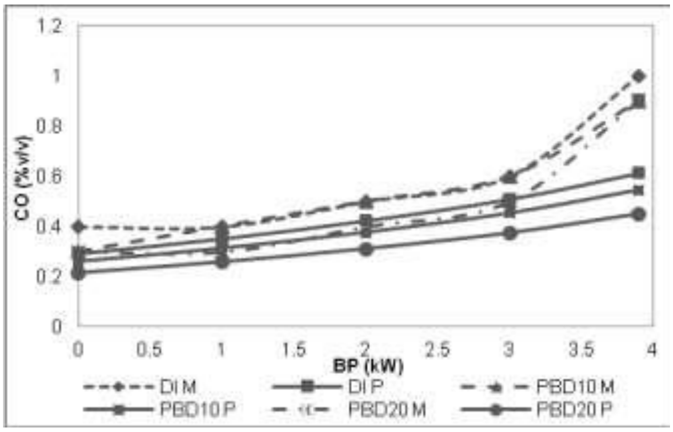

Fig.12: Measured and Predicted CO with 20% EGR

E. Smoke Emission

The smoke opacity of the exhaust gas is measured to quantify the particulate matter present in the exhaust gas. Figure 13 and figure 14 shows smoke variation with various EGR levels at no load and full load condition respectively. Higher smoke opacity of the exhaust is observed when the engine is operated with EGR compared to without EGR [3, 10, 12, 15, 17]. The variations in the smoke opacity level at high loads are higher compared to that at lower loads. EGR reduces availability of oxygen for combustion of fuel, which results in relatively incomplete combustion and increased formation of particulate matter. Smoke emissions are lower for bio-diesel blends compared to diesel at all load conditions irrespective of EGR level. PBD20 shows 25.75%, 13.5% average reduction in smoke compared to diesel fuel and PBD10 respectively. This is presumably due to good mixture formation and presence of oxygen in bio-diesel blends. The non linear regression equation for predicting CO emission is given in equation (7).

$$\ln(\text{smoke}) = 23.2 + (0.171\ W) + (0.0307\ EGR) - (0.00004\ CV) - (23.0\ FD) \quad (7)$$

The comparison of measured and predicted smoke emission vs EGR% for diesel, PBD10 and PBD20 at 25% load condition is shown in figure 15. Up to 15% EGR predicted and measured smoke are comparable for all three fuels. But at 20% EGR the variation is high, because at higher EGR level the oxygen deficiency inside the cylinder increases further which results in complete combustion and increased smoke emission.

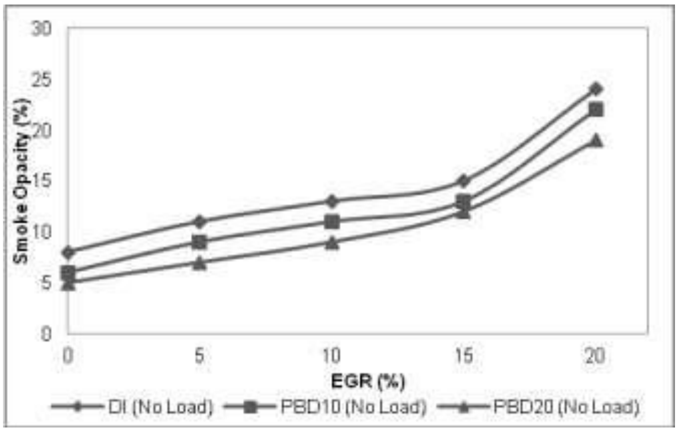

Fig.13: Comparison of smoke opacity with EGR (No load)

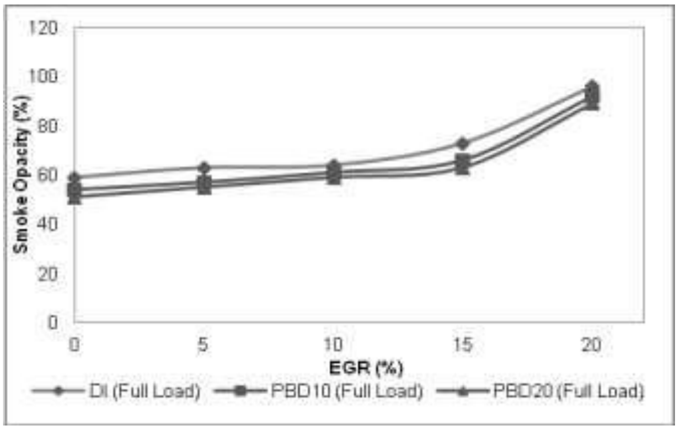

Fig. 14: Comparison of smoke opacity with EGR (Full load)

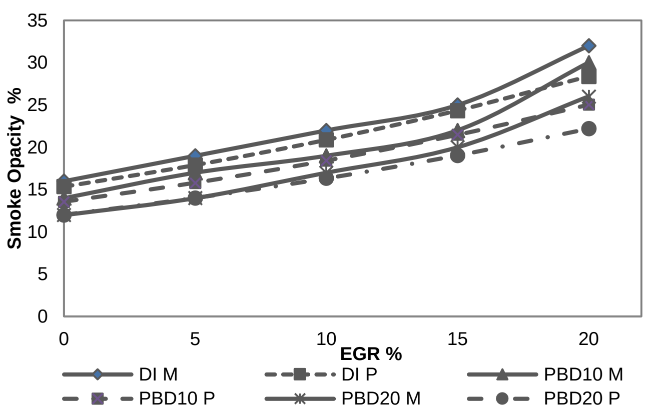

Fig.15: Measured and Predicted smoke opacity (25% load)

IV. CONCLUSION

A four stroke water cooled single cylinder direct injection diesel engine was run successfully using Diesel and Pongamia Bio-diesel blends (PBD10 and PBD20) as fuel for various proportions of EGR. The performance and emission characteristics have been analyzed and compared to baseline diesel fuel. The following conclusions are made with respect to the experimental and modeling results,

1. BTE of bio-diesel blends are found to be comparable with diesel, at all loads with and without EGR. At full load BTE of diesel, PBD10 and PBD20 are 34.76%, 34.27% and 34.03% with no EGR. The optimum EGR for the maximum BTE and the minimum BSFC is found to be 15%.
2. NO emission decreases with the increase in the percentage of EGR, but at a particular EGR percentage, NO decreases with the increase in the % of bio-diesel in the bio-diesel blend.
3. CO emissions are found to increase with the increase in the percentage of EGR. However at a particular EGR percentage, with the increase in the % of bio-diesel CO are found to decrease.
4. The increase in smoke at lower loads are insignificant with the increase in the percentage of EGR while at full load it also increases considerably with the increase in the percentage of bio-diesel.
5. Increasing EGR percentage beyond 15% can reduce NO further, but it will increase CO and smoke emission which is not acceptable. However the bio-diesel blends show lower emissions than diesel at a particular EGR percentage.
6. Multivariate non linear regression analysis is carried out to model the performance and emission parameters. Statistical analysis of these equations gives R^2 almost nearer to 0.95 except CO. Predicted values were compared with experimental data.
7. The performance and emission characteristics of diesel engine using similar fuel blends and EGR rates can be predicted without any expenses for experimentation with a correlation coefficient (R) in the range of 0.89-0.97.

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