Performance, Combustion and Emission Characteristics of A Diesel Engine Fuelled With The Aegle Marmelos Pyrolysis Biooil

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Abstract- *This paper presents the performance, combustion and emission characteristics of a bio-oil obtained from bael oil seed which is available across all over India. Pyrolysis was carried out between 450○C and 550○C under semi-batch type reactor for the production of bael pyrolysis oil. The yield of the bael pyrolysis oil was found to be about 40% at an optimum temperature of 500○C. The pyrolysis oil was also characterized for its suitability of using it as an alternative fuel for internal combustion engines. The combustion, performance, and emission behaviour of the diesel engine operated with the different bael pyrolysis biooil-diesel blends were assessed and compared with those of diesel operation at different loads. The results indicated that the engine brake thermal efficiency was increased by about 27% for bael pyrolysis bioil-diesel blend of 20 percentage operation from no load to full load operation in comparison to diesel. The Brake specific energy consumption gets decreased by 20% for the B20 blend ratio compared to the diesel at full load condition. As the bael pyrolysis bioil -diesel blend ratio increases, the lower NO emission was found to be about 28% for B20, in comparison with diesel at full load condition. From the obtained results, it is suggested that the 20% bael pyrolysis biooil blend can be considered as a potential candidate to be used as a fuel in compression ignition engines.*

Keywords- Bael seed, Pyrolysis, Brake thermal efficiency (BTE), Brake specific energy consumption (BSEC), NO emission.

I. INTRODUCTION

The demand in the energy source has been increased due to the exploitation of the fossil fuels. According to the Energy statistics 2017 given by the ministry of statistics and programme implementation the consumption of the petroleum product has been increased by 4.31% in the year 2016 compared to 2015[1].The emission of the greenhouse gases and impact in the global warming affects the environment and therefore there is a need of an alternative renewable energy sources. The bio fuels from the plant biomass are the solution to overcome the energy crisis in today's world and it also leads to the economic development of the country. Biomass is a solid waste agricultural product and it can be converted into the bio fuels through a various conversion process such as gasification, liquefaction, combustion and pyrolysis. Among them pyrolysis has gained attention because of the maximum yield of biooil with the by-products of solid char and non condensable gases.Pyrolysis is the thermal decomposition process of the biomass under the absence of oxygen. The biofuels obtained from biomass has the advantage of zero emission because of low sulphur and the nitrogen content.Aegle Marmelos is known as bael tree and it is widely grown in sub-Himalayan forest, west Bengal, middle India and Tamil Nadu.Aegle marmelos is a medium-sized tree and grow as much as twelve to fifteen meters, which comes under the rutaceac family. The oil content present in the bael seeds are about 40 to 50 percent [2].

The bio-oil composed of different qualities of hydrocarbon compounds and moisture content, and also acidic in nature. Most of the bio-oils are denser than diesel fuels but have low heating values. Also, the bio-oil requires a necessary pre-treatment to remove water content and neutralize before using it as an alter-native fuel in compression ignition (CI) engine. Many experiments have already been conducted to determine the performance and emission of a diesel engine run on bio-oil.Vikranth et al [3, 4] used the mustard cake pyrolytic oil blends in a diesel engine and found that 30% blend gave 4.7% higher brake thermal efficiency and lower exhaust emissions compared to diesel.

The utilization of bio-oil derived from pyrolysis of waste wood was investigated by Seokhwan Lee [5].in a diesel engine for replacement of petroleum fuel. S.Murugan [6] investigated on the tyre pyrolysis oil obtained from automobile tyres as a fuel in diesel engines. The 20 percentage of tyre pyrolysis oil gives better thermal efficiency compared to other blends.Debalaxmi Pradhan [7] conducted an experiment on the utilization of biooil derived from the pyrolysis of Mahua seed and found that the 30% blend gives a

better performance as a fuel in compression ignition engines. Many research works have been performed on minimizing the problems associated with the use of bio-oils in the CI engines. The continuous search for potential liquid alternative fuels for diesel engines has been carried out using various biomass feed stocks.

In this investigation, the biooil obtained by the pyrolysis process was pretreated for reducing its acidity and then blended with diesel at four different percentages from 10 to 20% on a volume basis in steps of 5% in the blend, and used as fuels in a single cylinder, four stroke, water-cooled direct injection (DI) diesel engine. The blends were denoted as B10, B15and B20 where the numeric value indicates the percentage of bael pyrolysis oil in the blend. The combustion, performance and emission parameters of the engine run on the three different bael pyrolysis oil-diesel blends were evaluated, compared with the diesel fuel operation and presented.

II. MATERIALS AND METHODS

2.1 Production of biooil:

The production of bael biooil was obtained from the lab scale fixed bed pyrolysis reactor.The schematic diagram of the reactor is shown in fig 1. Pyrolysis setup consists of a semi-batch stainless steel reactor having 17.5 cm length with the inside and outer diameter4.7 and 5 cm respectively. A lab scale fixed bed reactor with the capacity of 2kg shown in fig was used to conduct the pyrolysis process of bael deoiled cake. The contaminants present in the reactor were cleaned prior to the experiment. An electrical heater of 240V and 9.5A was employed to heat the sample in the absence of oxygen to raise the temperature of the sample. The PID controller coupled with K-type thermocouple was used to regulate the temperature of the reactor and the heating rate of 10°C has been adjusted with the help of dimmerstat.The gases evolved during the process was passed in the water cooled condenser which was placed at the outlet of the reactor. The gases are condensed to the liquid oil that are collected in the conical flask and some of the gases are non condensable which are collected in the bladder and the non condensable gases consists of some hydrocarbons and they are tested by GC analysis.
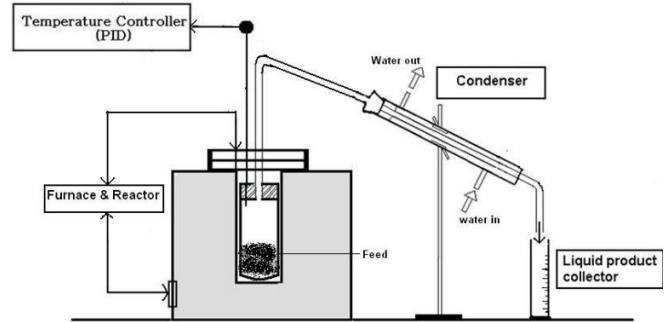

Fig 1 Fixed bed pyrolysis reactor

2.2 Engine experimental setup:

The experimental test rig consists of a variable compression ratio compression ignition engine, eddy current dynamometer as loading system, fuel supply system, water cooling system, lubrication system and various sensors and instruments integrated with computerized data acquisition system for online measurement of load, air and fuel flow rate, instantaneous cylinder pressure, injection pressure, position of crank angle, exhaust emissions and smoke opacity. Figure.2 represents the schematic representation of the experimental test setup.. The setup enables the evaluation of thermal performance and emission constituents of the VCR engine. The thermal performance parameters include brake power, brake mean effective pressure, brake thermal efficiency, volumetric efficiency, brake specific fuel consumption, exhaust gas temperature, heat equivalent of brake power and heat equivalent of exhaust gas. Commercially available lab view based Engine Performance Analysis software package IC Engine soft is used for on line performance evaluation.
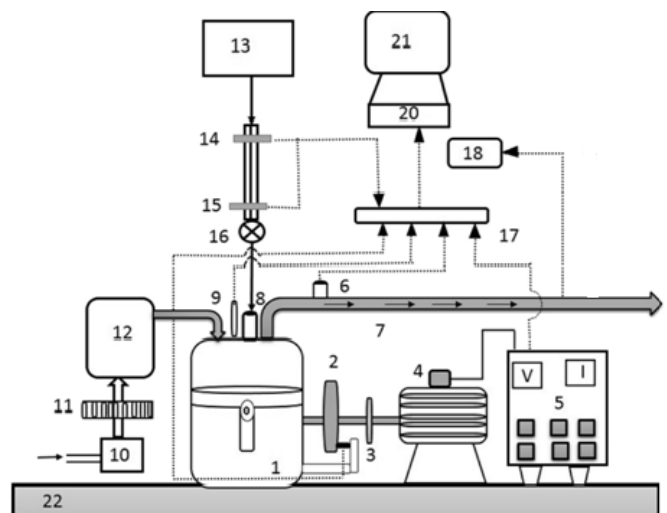

Fig.2 Engine Experimental setup. 1. Engine, 2. Fly wheel, 3. Speed sensor, 4. AC dynamometer, 5. Resistive load cell, 6. EGT sensor, 7. Exhaust manifold, 8. Fuel injector, 9. Pressure transducer, 10. Air filter, 11. Air flow sensor, 12. Air box, 13.

Fuel tank, 14. High fuel level optical sensor, 15. Low fuel level optical sensor, 16. Fuel pump, 17. Control panel, 18. Exhaust gas analyser, 20.Data acquisition system, 21. Monitor 22. Engine base.

The exhaust emissions of the engine are analysed using an exhaust gas analyser. The constituents of the exhaust gas measured are CO (%), CO_2 (%),O_2 (%), HC, (ppm), NOx (ppm) and SOx (ppm). Table 1 gives the technical specifications of different components used in the test rig.

Table 1 Specification of VCR engine test rig

ENGINE PARAMETERS	
Rated Power and Speed	3.5kW@1500rpm
Bore×Stroke	87.5mm×110mm
Compression ratio	17.5:1
Nozzle operating pressure(bar)	200
Injection timing (CA)	25° bTDC
Intake valve opening/closing	4.5°bTDC/35.5°aBDC
Exhaust value opening/closing	35.5°bBDC/4.5°aTDC

III. RESULTS AND DISCUSSION

3.1 Characterisation of Mahua bio-oil:

The pyrolysis reactor was maintained at different temperatures ranging from 450 to 550∘C for the determination of optimum temperature at which the maximum bio-oil yield from Mahua seed was obtained. Table 2 provides the details of pyrolysis products obtained from Mahua seed pyrolysis at different temperatures. It is evident from the table that the maximum bio-oil yield of 40% was obtained from bael seed at 500∘C. The maximum bio-oil yield at 500∘C can be attributed to thermal cracking, depolymerization, and recondensation of secondary reactions.

Table 2 Effect of temperature on product yield

Temperature range	Oil yield %	Char yield % %	Gas yield %
450	33	36	31
475	38	35.5	26.5
500	40	32	28
525	37	36	27
550	35	39	26

The obtained bael pyrolysis oil is a dark brown organic oil comprising different molecular weight compounds in it. The physical properties such as density, kinematic viscosity, flash point, fire point, pour point and cetane number are determined as per the ASTM standards. These important physical properties of bio-oil in comparison with diesel are listed in table 3.

Table 3 Physical properties of Bael biooil in comparison with Diesel.

Properties	ASTM method	Diesel	BAEL BIOOIL
Density @40°C (kg/m³)	ASTM D 1298	833	921.3
Kinematic Viscosity @ 40 oC (cSt)	ASTM D 445	2.58	23.19
Calorific value (MJ/kg)	ASTM D 4809	43.8	41.8
Flash Point (°C)	ASTM D 3828	50	84
Fire point (°C)	ASTM D 92	56	118
Cetane number	ASTM D 976	50	37.7

3.2 Performance parameters:

3.2.1 Brake Thermal Efficiency (BTE):

The variation of brake thermal efficiency with load for diesel and different bael pyrolysis oil-diesel blends is shown in fig 3. The BTE increases steadily with engine load for all the tested fuels. The fuel consumption rate gets increased as the load increases.It can be observed that the brake thermal efficiencies are closer to each other except the B10CR16 blend. A maximum of 29% BTE is found for B20 at full load. It is found that the 27% increase in brake thermal efficiency for B20 compared to the diesel at full load condition. The rate of fuel consumption is higher for the blends, and it is found the maximum for the B20CR16 blend. The high viscosity and density of blends may cause higher fuel consumption. BTE is the ratio of brake power to the input energy of the fuel which is the product of fuel flow rate and calorific value. The calorific value of the blends decreases with the percentage increase of bio-oil in the blend. Due to the less amount of fuel consumption as the biooil blend ratio increases the BTE of the engine is greater for the biooil blends compared to the diesel.
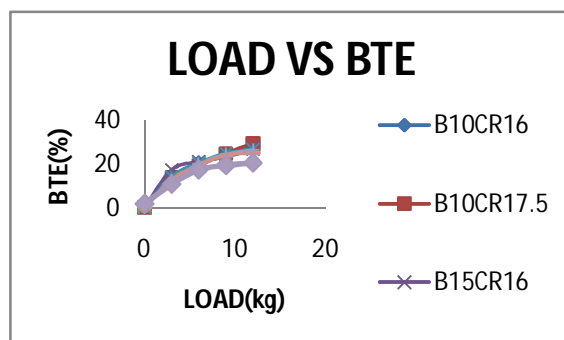

Fig.3 Variation of Brake thermal efficiency for different loads.

3.2.2 Brake specific energy consumption (BSEC):

Fuels with different calorific value and density are not comparable with brake specific fuel consumption (BSFC). Hence, BSEC is used which is the product of BSFC and calorific value. Fig. 4 shows the variation of BSEC with load for various test fuels in this study. The BSEC was found to be 17.52 MJ/kWh for diesel at full load. For the B10 B15 and B20 of the compression ratio 17.5 blends is 12.22, 13.47 and 13.87 MJ/kWh respectively. BSEC decreases with the increase in the load for all the test fuels as expected. The BSEC increases for the bael pyrolysis oil-diesel blends compared to that of diesel for all loads due to the lower calorific value of the blends. At full load condition the B20CR17.5 blend shows the maximum BSEC because of the lower calorific value and the increased amount of fuel injection.
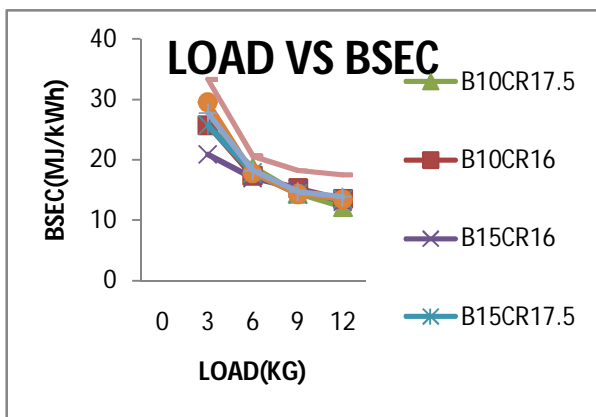

Fig.4 Variation of Brake specific energy consumption for different loads.

3.3 Combustion Parameters:

3.3.1 Cylinder Pressure:

The variation of cylinder pressure with crank angle at full load for the test fuels is shown in fig 5 .The cylinder pressure of the CI engine depends on upon the mass fraction of fuel burned during the premixed phase or uncontrolled phase of combustion. This is governed mainly by the ignition delay and sprays developed by the injected fuel. The premixed phase combustion can be measured by the accumulated fuel quantity during the ignition delay period. The volatility and viscosity of the fuel play a significant role in the atomization rate and air/fuel mixture formation. It is clear from the figure that the maximum pressure is obtained for the B20 diesel blend. The rate of pressure rise has been increased because of the higher ignition delay. Due to the higher density of the bael pyrolysis oil, the fuel accumulated in the premixed combustion phase is higher than that of diesel. Increase in the cylinder pressure suppresses the dissociation of the

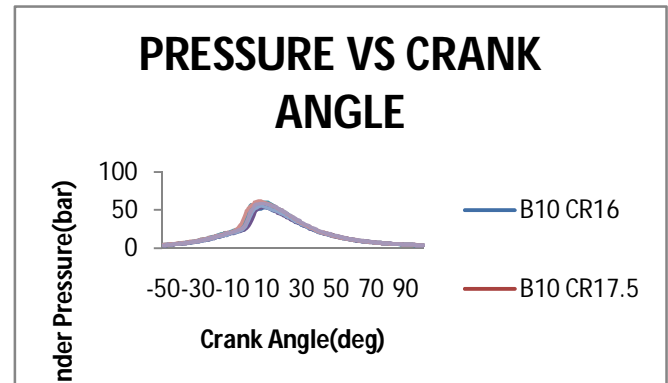combustion products and it will result in the incomplete combustion.

Fig.5 Variation of Cylinder pressure with Crank angle.

3.3.2 Heat release rate:

The amount of heat added to the engine cylinder can be computed by the heat release analysis based on the combustion pressure data. The HRR was obtained by performing the first law of thermodynamic analysis of pressure crank angle data proposed by Heywood [8]

$$\frac{dQch}{d\theta} = \frac{\gamma}{\gamma-1}p\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dp}{d\theta} + \frac{dQht}{d\theta}$$

Where $\frac{dQch}{d\theta}$ is gross heat release rate (J/CA), V = cylinder volume (m^3), P = in-cylinder pressure (bar), θ = crank angle degree, $\frac{dQht}{d\theta}$ = rate of heat transfer from the wall (J/CA).

The cylinder pressure data from 200 consecutive cycles were recorded on a high-speed computer connected to the digital data acquisition system and then averaged. Fig. 6 depicts the variation of the heat release rate with crank angle at full load for diesel and the bael pyrolysis oil-diesel blends. The HRR is slightly negative during the ignition delay period due to the cylinder heat transfer losses and the cooling effect of the fuel vaporization. The HRR is the highest for B15 blend followed by other bael pyrolysis blends and the diesel. The HRR of the higher bael pyrolysis oil blend ratio is decreased due to the accumulation of the fuel inside the cylinder which results in the unburned gases. The heat for the unburned gases was not recovered due to the ignition delay. The maximum HRR for diesel, B10, B15 and B20 are by about 55, 59, 62 and 52 J/kg respectively, at full load
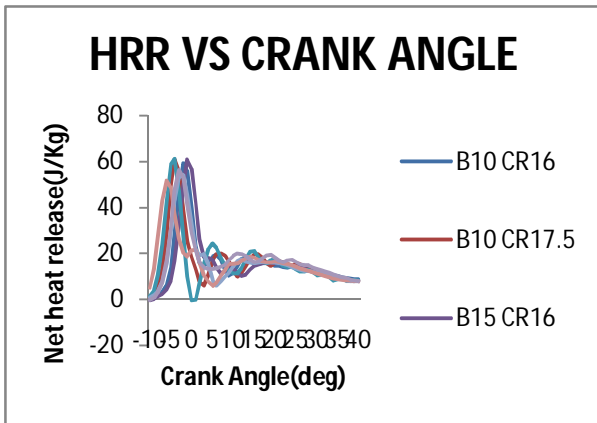
Fig.6 Variation of Net heat release with Crank angle

3.4 Emission Parameters:

3.4.1 Carbon monoxide (CO) emission:

Fig.7 shows the variation of CO emission with load for diesel and the bael pyrolysis oil blends. The intermediate product of combustion is CO, formed mainly due to the incomplete oxidation of the fuel during combustion. If the combustion is complete, then CO is converted to CO_2. In general, the CO emissions is less in CI engines than in SI engines, which is due to the lean operation of air/ fuel mixture in CI engines. As the load increases the rate of fuel consumptions gets increased which results in the formation of more amount of CO emission. The fuel air mixture becomes rich as the load increases and it leads to the incomplete combustion of the fuel. The emissions CO is lower in the case of bael pyrolysis oil -diesel blends compared to that of diesel operation at full load, which is due to lower calorific value of fuel which overcomes the incomplete oxidation. The higher viscosity of the MPO-diesel blends might result in long spray penetration, large fuel droplets and poor atomization results in lower CO emissions. The CO emission for diesel, B10, B15 and B20 are 0.33, 0.3, 0.26 and 0.75 % respectively at full load condition.
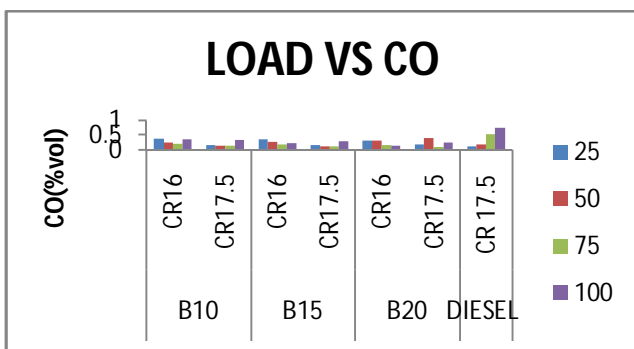

Fig.7 Variation of CO emission with different loads

3.4.2 Hydrocarbon (HC) emission:

Incomplete combustion of the fuel results in hydrocarbon (HC) emission. In IC engine, the HC emissions were formed due to poor fuel volatility, improper atomization of the fuel, the high viscosity of the fuel and flame quenching at walls of the combustion chamber. Fig 8 shows the variation of HC emission with load for diesel and the bael pyrolysis oil-diesel blends. In this study, the HC emission increases with the increase in load for all the test fuels. The HC emission is lower for the bael pyrolysis oil -diesel blends compared to that of diesel for all the engine operation. The increase in the bio-oil percentage results in a lower HC emission which is due to high viscosity and lower heating value caused by poor atomization of the fuel. The HC emissions for diesel, B10, B15 and B20 are 524, 201,143 and 78 ppm respectively, at full load. A lower HC emission is noticed for the bael pyrolysis oil-diesel blends than for diesel which may be due to improper spray caused by higher viscosity, the presence of unsaturated hydrocarbons in the bael oil, which are unbreakable during the combustion process.
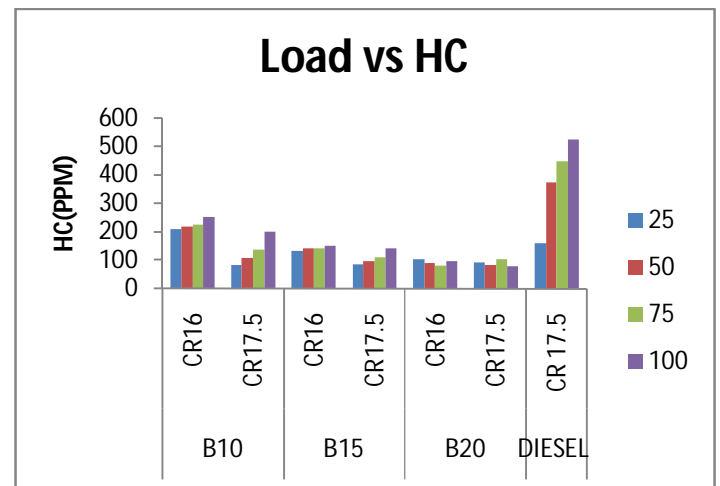

Fig.8 Variation of HC emission with different loads

3.4.3 Nitric oxide (NO) emission:

The nitric oxide (NO) emission is a strong function of temperature, pressure and total oxygen concentration in the combustion chamber. The increase in the gas temperature with loads results in higher NO emission for all the tested fuels. The variations of the NO emission with load for diesel and the bael pyrolysis oil -diesel blends are shown in fig 9. The NO emission for diesel, B10, B15 and B20 are 1650, 1437, 1501 and 1185 ppm respectively, at full load. The lower values of the NO emission for the bio-oil blends than that of diesel may be due to the lower HRR.The higher ignition delay causes the hot gases from combustion have a higher exchange surface with the cylinder and thus a lower temperature. As mentioned

previously that bio-oil contains high moisture content which may reduce the cylinder gas temperature.
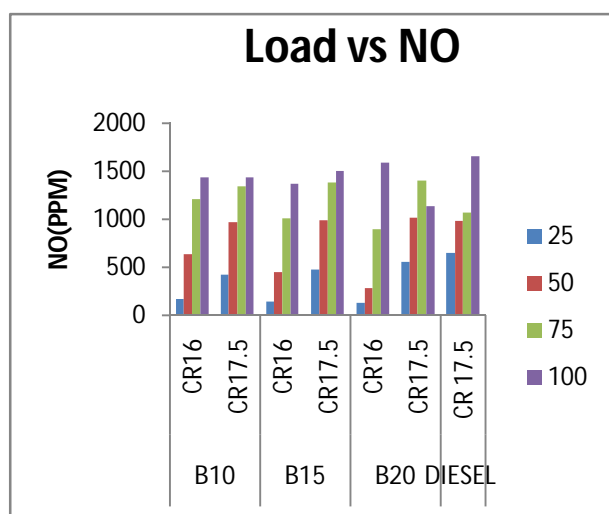

Fig.9 Variation of NO emission with different loads

IV. CONCLUSION

The combustion, performance, and emission characteristics of a DI diesel engine fuelled with the bael pyrolysis biooil-diesel blends were experimentally investigated. The pyrolysis experiments were carried out in between 450 and 500°C with a heating rate of 20°C/min. The optimum bio-oil yield of 40% obtained at 500°C. The high viscous and low cetane bael pyrolysis biooil is not suitable for direct utilization in a diesel engine, but it can be used only in the blended form by emulsion process with diesel without any engine modification. The combustion of bael pyrolysis biooil - diesel blends is slower than that of diesel is due to the low cetane number, higher density, and poor volatility. The HC and CO emissions were lower for the bael pyrolysis biooil - diesel blends than diesel. The lower NO emission was found to be about 28% for B20, in comparison with diesel at full load due to increased ignition delay. At full load condition, it is found that the 27% increase in brake thermal efficiency for B20 compared to the diesel. From this experimental investigation, it is recommended that up to 20% bio-oil blend can be used in the diesel engine for better performance and minimizing the emission to the environment.

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