https://dx.doi.org/10.22161/ijaers.6.4.31 ISSN: 2349-6495(P) | 2456-1908(O)

# Reduction of Emissions from Common-rail Diesel Engine using Mahua and Pongamia Methyl Esters

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***Abstract*— *In this study, the performance, emission and combustion characteristics of two different biodiesel blends produced from Mahua and pongamia methyl esters were compared with conventional diesel fuel. Methyl esters for experiment were produced by using a catalytic transesterification process and, compared the properties with ASTM standard values of biodiesel fuel and diesel fuel. The experiments were performed in a four stroke, single cylinder, common rail direct injection (CRDI) system assisted diesel engine at a constant speed of 1500rpm with varying injection pressure. During the tests, the specific fuel consumption, brake thermal efficiency, combustion and exhaust emissions of the CRDI diesel engine were measured. From the results it is clear that the HC, CO and smoke levels are drastically reduced when using the methyl ester blends. Especially in the case of MME20, NOx emissions was minimum when compared with other blends and it also found less amount of other harmful emissions like HC, CO and smoke.*

***Keywords*— *Common rail direct injection (CRDI), Catalytic transesterification, Mahua methyl ester (MME), Pongamia methyl ester (PME), Emissions, Combustion.***

**Nomenclature**

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| BSFC | Brake specific fuel consumption, kg/kWh |
| BP | Brake power, kW |
| BTE | Brake thermal efficiency, % |
| CO | Carbon monoxide, % |
| HC | Hydrocarbon, ppm |
| $NO_x$ | Oxides of Nitrogen, ppm |
| CRDI | Common rail direct injection |
| rpm | Revolution per minute |
| MME | Mahua methyl ester |
| PME | Pongamia methyl ester |
| MME20 | Mahua methyl ester 20% + Diesel fuel 80% |
| MME40 | Mahua methyl ester 40% + Diesel fuel 60% |
| PME20 | Pongamia methyl ester 20% + Diesel fuel 80% |
| PME40 | Pongamia methyl ester 40% + Diesel fuel 60% |

## I. INTRODUCTION

Biodiesel is getting hold of increasingly important as a smart fuel due to the depleting fossil fuel sources. Chemically, the biodiesel is monoalkyl esters of long chain fatty acids derived from raw vegetable oils [1]. Biodiesel has several benefits such as it is non-toxic, biodegradable, low emissions and is a renewable source. Additionally, biodiesel does not contribute to the rise in carbon dioxide levels in the environment and thus reduces the amount of the greenhouse effect [2]. Two most important processes have been investigated to overcome these drawbacks and let the raw vegetable oils to be utilized as an alternative fuel: Pyrolysis and transesterification. Pyrolysis is a chemical decay of organic elements caused by the use of thermal energy in the absence of oxygen. Many researchers have studied the Pyrolysis of vegetable oils with the aim of obtaining biodiesel suitable for CI engines. Thermal decay of vegetable oil (triglycerides) produces compounds, including carboxylic acids, alkadienes, alkanes, alkenes and aromatics. Different types of vegetable oils depict big differences in composition when they are thermo-chemically decomposed. The pyrolyzed vegetable oils chemically similar to petroleum derived diesel fuel [3-7]. Transesterification is a chemical process between triglycerides of vegetable oil and alcohol (i.e. methanol or ethanol) in the presence of catalyst to obtain methyl or ethyl ester and glycerol as by product. The transesterification process generally depends upon the amount of alcohol, catalyst, time, water and FFA. Vegetable oils with huge amount of FFA are difficult to pass through the transesterification process because it will produce soap formation in the presence of the alkali catalyst [8,9]. The FFA additionally prevents the separation of methyl ester from glycerol layer. The di-glycerides are the intermediates in this chemical process. The glycerol layer settles at the base of the vessel. The mechanism of transesterification process is shown in Figure 1.

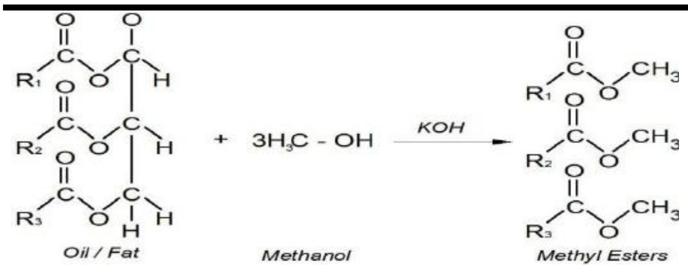

*Fig.1: Mechanism of transesterification process*

Biodiesel fuel generally includes a little amount of di-glycerides having an advanced boiling point than the diesel fuel. These complex chemical bonds led to the configuration of gases of short molecular weight and thus volatile chemical compounds ignited in advance and reduced the delay period [10-12]. Many researchers have done experiments on the performance and emissions of a DI diesel engine operating with different biodiesel blends. They found biodiesel fuels produced lower harmful pollutant emissions such as CO, HC and PM emissions, and slightly higher $NO_2$ and $NO_x$ emissions [13-17]. The oxides of nitrogen are the most harmful parameter that affect the environment through acid rain, human diseases, etc.,. Also, CO and $NO_x$ are primary pollutants in the formation of troposphere ozone, which are the important greenhouse gases. Many researchers have found that the 20% and 40% biodiesel blends produced low emissions of HC, CO, NOx and PM, compared with other biodiesel blends [18-22]. For the present investigation biodiesel are prepared from Mahua oil and pongamia pinnata oil through catalytic transesterification method. The properties of both methyl esters thus obtained are compared to ASTM biodiesel standards. According to literature survey, MME20, MME40, PME20 and PME40 blends are used for experiment. The performance, emission and combustion characteristics of a four stroke, single cylinder, common rail direct injection (CRDI) diesel engine was analyzed using different methyl ester (MME, PME) blends to find out the suitable methyl ester blend.

## II. THE BIODIESEL PRODUCTION

There are many admitted technologies that have been employed for the production of biofuel. Vegetable oils are apposite to be customized in order to reduce their densities and viscosities, so that the product obtained has appropriate properties to be used as fuels for diesel engine [3]. Transesterification is the process of using an alcohol in the presence of a catalyst such as potassium hydroxide or sodium hydroxide, to break the molecule of the raw vegetable oil into ethyl or methyl esters, with glycerin as a by-product. The potassium hydroxide (7g/lit) is dissolved into methanol as catalyst in a biodiesel reactor. Then, the catalyst/methanol mixture is mixed with the raw vegetable oil (i.e., pungamia and Mahua). The final mixture is stirred vigorously for one hour at 60˚C in ambient pressure. A successful transesterification produces two different liquid phases, methyl ester and crude glycerin. Crude glycerin is the heavier liquid, will accumulate at the bottom later than some hours of settling. Phase separation completed within 2-3 hours of settling. Complete settling of methyl ester can take as long as 8-10 hours. Washing the methyl ester is a two step process. A water wash solution at the rate of 26% by volume of vegetable oil and 1 gram of tannic acid / liter of water is added to the methyl ester and stirred. This process is continued until the methyl ester becomes clear. After transesterification, the viscosity of both methyl esters was found to be reduced, which is nearer to the diesel fuel as given in the Table 1**.** Prepared methyl esters (MME & PME) were then blended with neat diesel in various concentrations for making biodiesel blends to be used in the CRDI diesel engine for conducting engine tests. The schematic diagram of biodiesel plant is shown in Figure 2.

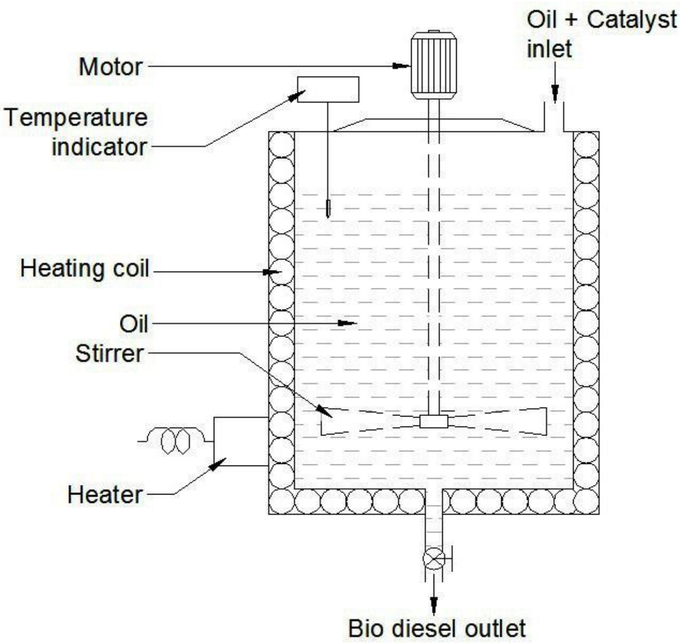

*Fig.2: Schematic diagram of biodiesel plant*

### 2.1 Properties of biodiesel

The properties of MME and PME in comparison with those of Biodiesel standards (ASTM) and the properties of biodiesel blends (MME20, MME40, PME20 and PME40) are compared with the neat diesel are shown in Table 2. The present results show that the transesterification process improved the fuel properties of the Mahua and pongamia oil with respect to viscosity (cSt), density (kg/m3), flash point (˚C), cetane number and the calorific value (kJ/kg). Comparison of these properties with the diesel fuel shows that the Mahua methyl ester (MME) and Pungamia methyl ester (PME) have closer fuel properties to that of diesel.

https://dx.doi.org/10.22161/ijaers.6.4.31 ISSN: 2349-6495(P) | 2456-1908(O)

*Table.1: Properties of biodiesel samples*

| Properties of fuel | Unit | Biodiesel standards (ASTM) | Mahua methyl ester (MME) | Pongamia methyl ester (PME) |
|---|---|---|---|---|
| Viscosity at 40ºC | cSt | 1.9-6 | 4.9 | 5.4 |
| Density at 15°C | kg/m$^3$ | 850-900 | 869.8 | 875.2 |
| Flash Point | °C | >130 | 136 | 148 |
| Calorific value | KJ/Kg-K | ≥36000 | 39950 | 37980 |
| Cetane number | - | 47 to 65 | 54.8 | 56.9 |

*Table.2: Properties of diesel - biodiesel blend samples*

| Properties of fuel | Unit | Diesel | MME20 | MME40 | PME20 | PME40 |
|---|---|---|---|---|---|---|
| Viscosity at 40ºC | cSt | 3 | 3.17 | 3.36 | 3.25 | 3.53 |
| Density at 15°C | kg/m$^3$ | 815 | 819.4 | 824.7 | 822.9 | 829.1 |
| Flash Point | °C | 56 | 66 | 78 | 72 | 96 |
| Calorific value | KJ/Kg-K | 42000 | 41440 | 40920 | 41280 | 40360 |
| Cetane number | - | 42.8 | 45.1 | 47.4 | 45.7 | 48.5 |

## III. EXPERIMENTAL SETUP AND TEST PROCEDURE

Experiments were conducted on Kirloskar AV1, four stroke, single cylinder and air cooled diesel engine assisted by common rail direct injection system. The rated power of the engine was 3.7 kW. The engine was operated at a constant speed of 1500 rpm. By adjusting the injection pressure from 250 to 500 bar, the engine speed was maintained when the load increased. Injection duration of the fuel injected into combustion chamber should be maintained as constant 750µsec for all loads. The engine was initially fuelled with diesel fuel to provide the baseline data and then, it was fuelled with diesel and carbon multiwalled nanoparticles blended fuel in two different proportions. Details of the engine specification are given in Table 3 and injector fuel specification in Table 4. The fuel flow rate is obtained on the gravimetric basis and the airflow rate is obtained on the volumetric basis. Eddy current dynamometer was used for loading the engine. AVL di-gas analyzer is used to measure HC, CO and $NO_x$ emissions. The specifications of the AVL di-gas analyzer is given in Table 5. The AVL smoke meter is used to measure the smoke density and the details of smoke meter is given in Table 6. The engine cylinder pressure and heat release rate were obtained by using data acquisition system interfacing with dual core processor. A burette is used to measure the fuel consumption for a specified time interval. The experimental setup is indicated in Fig.3.

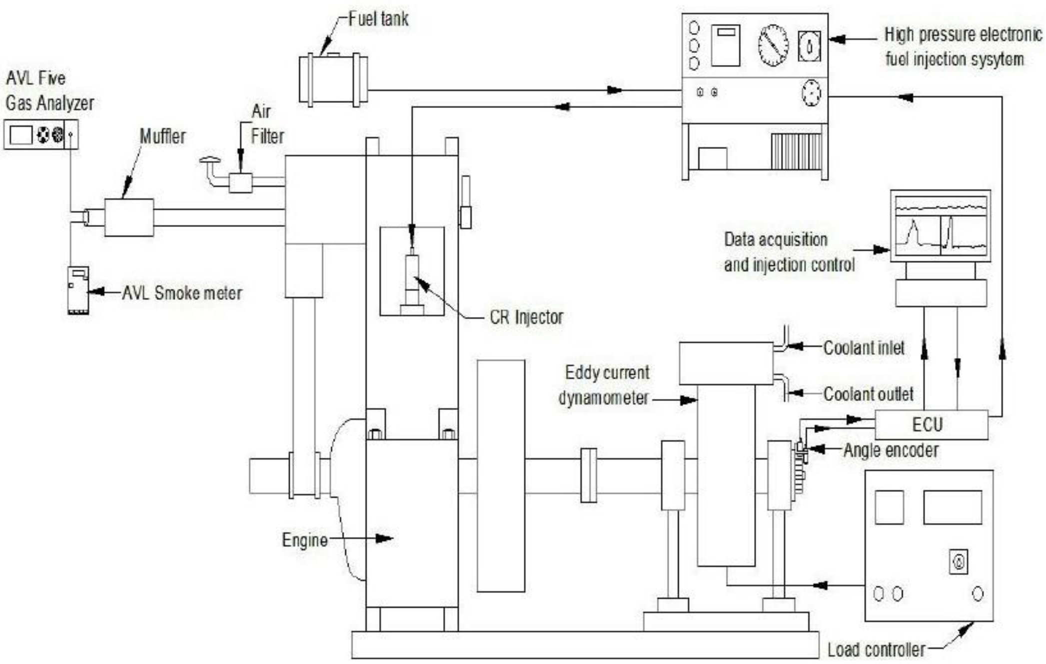


*Fig.3: Experimental setup*

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*Table.3: Engine specification*

| | | |
|---|---|---|
| Type | : | Vertical, water cooled, four stroke |
| Number of cylinders | : | One |
| Bore | : | 87.5 mm |
| Stroke | : | 110 mm |
| Compression ratio | : | 17.5:1 |
| Maximum power | : | 3.7 kW |
| Speed | : | 1500 rev/min |
| Dynamometer | : | Eddy current |
| Injection timing | : | 23° (before TDC) |
| Injection pressure | : | 250-500 kgf/cm$^2$ |

*Table.4: Injector fuel system specifications*

| Fuel fed | Units | Common rail |
|---|---|---|
| Injection pressure | MPa | 250-600 MPa |
| Number of nozzle holes | - | 3 |
| Nozzle hole diameter | mm | 0.518 |
| Start of injection | - | 23° Before top dead center (BTDC) |
| Injection duration | μsec | 750 |
| Fuel injected | g/cycle | 0.168 (at full load) |

*Table.5: Specifications of AVL Di gas analyzer*

| Make | AVL |
|---|---|
| Type | AVL Di Gas 444 |
| Power Supply | 11...22 volage ≈ 25 W |
| Warm up time | ≈ 7 min |
| Connector gas in | ≈ 180 I/h, max.overpressure 450 hPa |
| Response time | $T_{95} \leq 15s$ |
| Operating temperature | 5...45 °C |
| Storage temperature | 0...50 °C |
| Relative humidity | ≤ 95%, non-condensing |
| Inclination | 0...90°∠ |
| Dimension (w x d x h) | 270 x 320 x 85 mm$^3$ |
| Weight | 4.5 kg net weight without accessories |
| Interfaces | RS 232 C, Pick up, oil temperature probe |

*Table.6: Specifications of the Smoke Meter*

| | |
|---|---|
| Make | AVL 437 Smoke meter |
| Type | IP 52 |
| Accuracy and reproducibility | ± 1 % full scale reading |
| Measuring range | 0 to 100 opacity in % |
| | 0 to 99.99 absorption m$^{-1}$ |
| Measurement chamber | Effective length 0.430 m ± 0.005m |
| Heating time | 220 V approximately 20 min. |
| Light source | Halogen bulb 12 V/5W |
| Maximum smoke temperature | 250 °C |
| Power supply | 190 – 240 V AC, 50 Hz, 2.5 A |
| Dimensions | 570mm × 500mm × 1250mm |

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## IV. RESULTS AND DISCUSSION

The engine operation was found to be smooth throughout all the load conditions, without any operational problems for Mahua and Pongamia methyl esters blended diesel fuel. In the present section, the performance attributes such as brake thermal efficiency, specific fuel consumption and the emission characteristics such as $NO_x$, CO, HC and smoke density are plotted against brake power. Based on the combustion data, heat release rate and in-cylinder pressure are plotted against crank angle.

### 5.1 Engine performance

### 5.1.1 Brake specific fuel consumption

Brake specific fuel consumption (BSFC) is the ratio between the mass of fuel consumption with the brake power. The variation of specific fuel consumption with respect to brake power is shown in Fig. 4. As seen in the figure, when fuelling with the methyl ester blends, the BSFC are increased compared with the diesel fuel, which is in agreement with the many literature [11,14,17,22]. Increase in the BSFC is not caused by any loss in efficiency of biodiesel. It is seen that BSFC is highest for methyl ester blends and lowest for neat diesel because of higher viscosity and lower volatility. From the figure it is shown that the BSFC values of neat diesel fuel and MME20 blend fuel are nearly same, while the MME40 and PME40 blends shows a considerable increase of about 4.29% and 7.43% in comparison with the diesel.

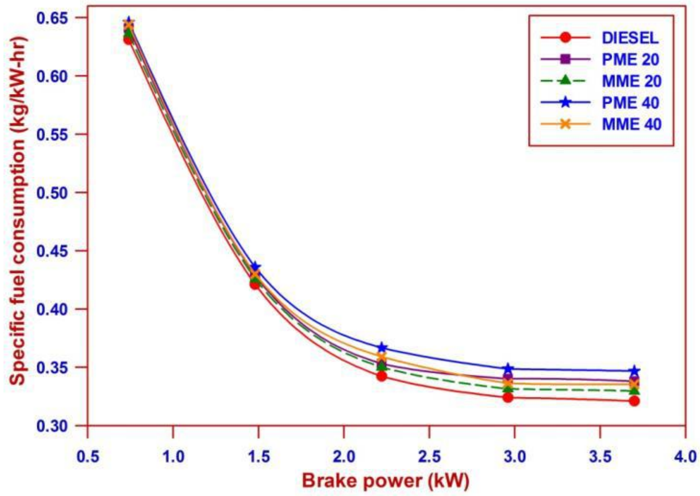


*Fig.4: Specific fuel consumption against brake power*

### 5.1.2 Brake thermal efficiency

Brake thermal efficiency (BTE) is more suitable than specific fuel consumption to evaluate the performance of different biodiesel fuels, in addition to their heating value. From the Fig. 5 it is clear that BTE increases with increase in, load up to part load and then decrease at full load due to the incomplete combustion of fuel. A number of research have been carried out and found to report that the increase in brake thermal efficiency when using the biodiesel in diesel engine [16,23,24]. Brake thermal efficiency values of MME20 and PME20 blends are nearly same to the diesel fuel. From the figure, the BTE slightly increased with the increasing proportion of the biodiesel fuel. The maximum increase of BTE was found in MME40 by about 1.31%.

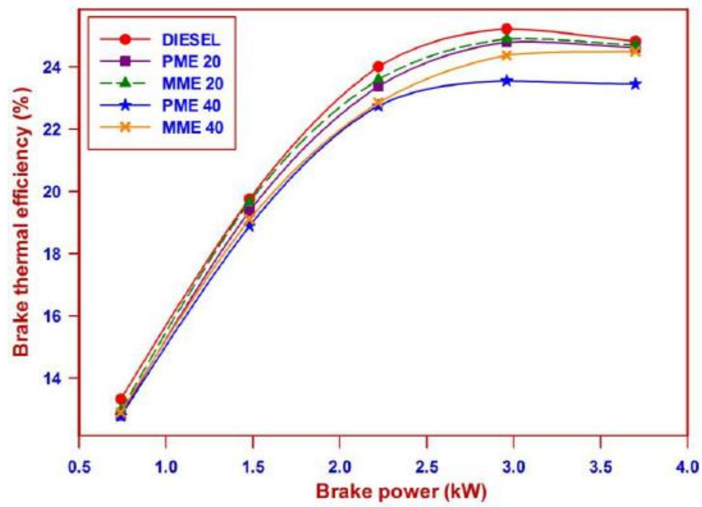


*Fig. 5: Brake thermal efficiency against brake power*

https://dx.doi.org/10.22161/ijaers.6.4.31 *ISSN: 2349-6495(P) | 2456-1908(O)*

**5.2 Emission parameters**

**5.2.1 Oxides of nitrogen**

The oxides of nitrogen ($NO_x$) emissions of the diesel engine is mainly depends on the flame temperature and oxygen content present in the fuel. The start of combustion was advanced with the methyl ester blends, which tends to an increase in mean temperature peak [22]. As seen in Fig. 6, the NOx emissions through the constant rpm band increased 4.60%, 9.31%, 10.99% and 11.33% for the MME20, PME20, MME40 and PME40 blends, respectively, compared with the neat diesel fuel. From the figure it can be seen that NOx emissions for methyl ester blends are highest when compared to neat diesel fuel, which is in conformity with the report of K. Nantha Gopal et al. [25] and K. Sureshkumar et al. [26]. It also can be seen that the NOx emissions of MME40 and PME40 are nearly similar values.

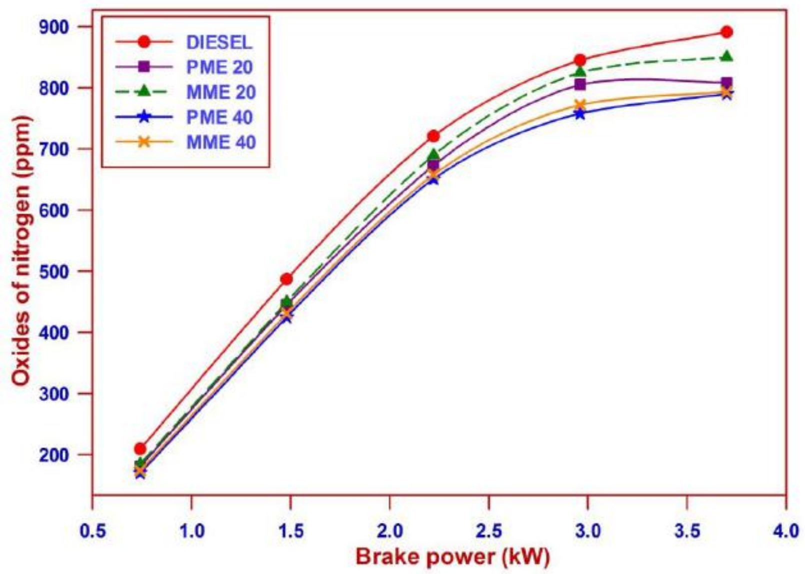


*Fig.6: Oxides of nitrogen against brake power*

**5.2.2 Carbon monoxide**

The variation of carbon monoxide (CO) emission by running CRDI diesel engine using Mahua methyl ester blends and pungamia methyl ester blends with neat diesel fuel is shown in Fig 7. It is observed that CO emission initially decreases at inferior loads up to 30% and then increases significantly for all the biodiesel-diesel blended fuels. Increased biodiesel blends cetane number, the least chance of fuel-rich zones formation, generally related to CO emission [12]. From the perception of excess oxygen present in the biodiesel, it helps to lean combustion compared with the neat diesel fuel combustion. From the figure, it is shown that the usage of biodiesel blends instead of neat diesel resulted in a 3.84%, 5.66%, 8.08% and 12.28% average decrease when fuelling with the MME20, PME20, MME40 and PME40, respectively.

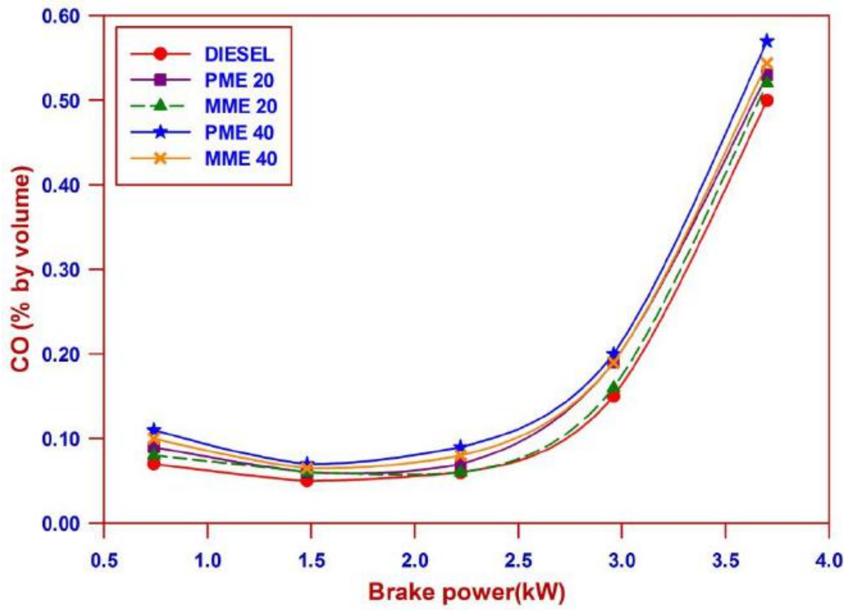


*Fig.7: CO against brake power*

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**5.2.3 Hydrocarbon**

The variation of hydrocarbon (HC) emissions with brake power is shown in Fig. 8. The blends of methyl esters with diesel fuel considerably decrease the HC emissions when compared with neat diesel. Methyl esters naturally contain rich oxygen content that increases the HC oxidation. From the figure, it is seen that the HC emission decreased with the increase of percentage of methyl esters with diesel fuel. Hydrocarbon emissions for MME20, MME40 were 105, 113 and 110, 118 ppm for PME20, PME40 blends, respectively. Compared with pongamia methyl ester, Mahua methyl ester reduces the HC emissions effectively.

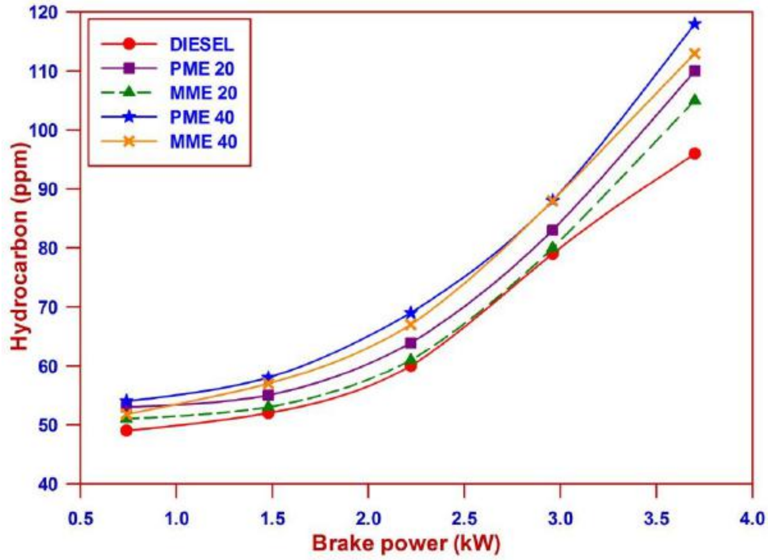


*Fig. 8: HC against brake power*

**5.2.4 Smoke opacity**

The formation of smoke is mainly depends on the partial burning of the liquid fuel and the incompletely reacted carbon present in the fuel [21]. Fig. 9 shows the variant of smoke opacity for Mahua, pongamia methyl ester blends and diesel fuel over the entire series of the brake power. As it was given in Fig. 9, the smoke emission reduced by the rise in biodiesel percentage. The mixing of biodiesel blend with air, producing locally rich regions of oxygen to prevent the crucial smoke formation. The smoke emission over the constant rpm band decreased 1.82%, 3.44%, 5.02% and 7.03% for the MME20, PME20, MME40 and PME40 blends, respectively, compared with the neat diesel fuel.

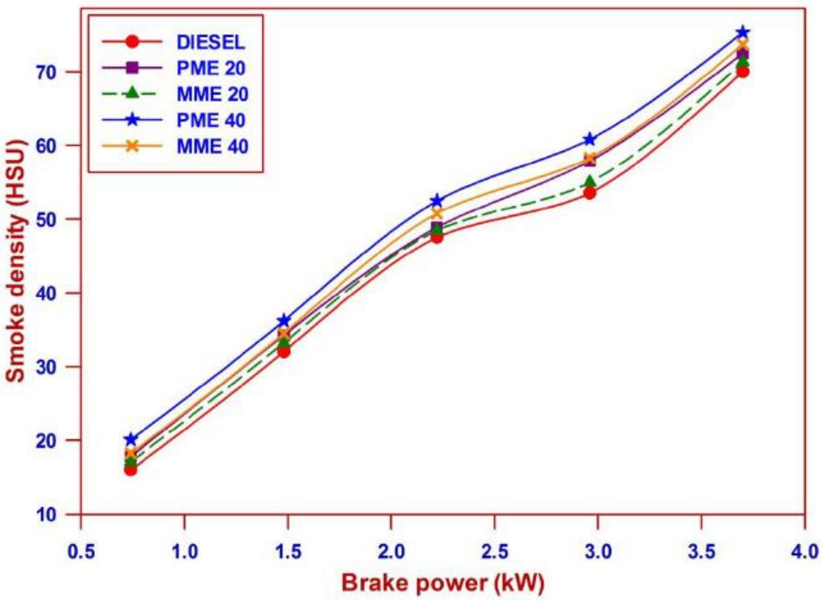


*Fig.9: Smoke density against brake power*

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**5.3 Combustion characteristics**

**5.3.1 Cylinder pressure**

The peak pressure of Mahua and pongamia methyl ester blends, and diesel fuel at full load condition is shown in Fig. 10. As a result of the shorter delay, maximum cylinder pressure occurs earlier for methyl ester blends in comparison with neat diesel. This is for the reason that the higher oxygen content in methyl esters are sufficient to make complete combustion of the fuel during the pre combustion phase and maintain to burn in the main combustion phase. It can be seen from the figure that MME40 had an 7.17% higher peak pressure than that of diesel fuel followed by PME40 (7.97%), MME20 (2.79%) and PME20 (4.26%). The similar tendency is observed during the whole range of engine operation at no load and part load conditions for all the test fuels.

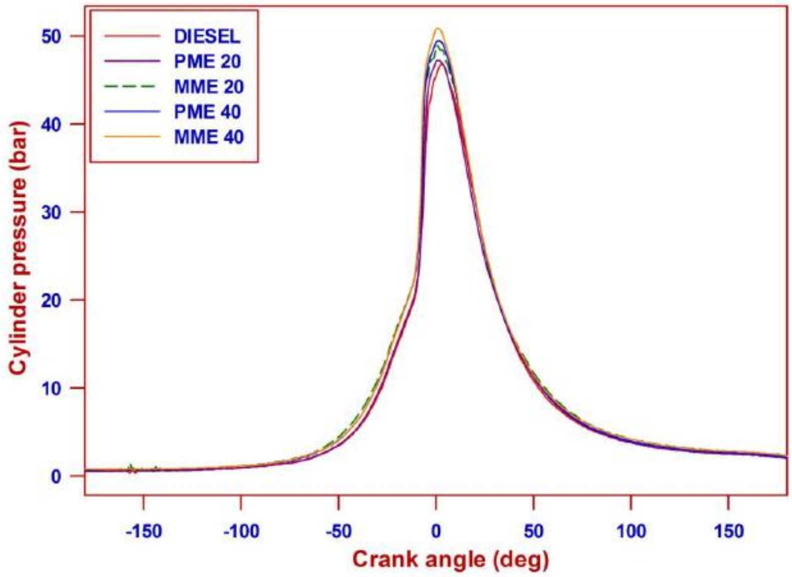


*Fig.10: Cylinder pressure against crank angle*

**5.3.2 Heat release rate**

The heat release rate (HRR) at certain operating points of different biodiesel-diesel blended fuels and diesel fuel operation are shown in Fig. 11. The figure shows HRR representing that the ignition delay for biodiesel blends was shorter than that for neat diesel. Many researchers intend that the combustion process is advanced as a result of the advanced injection with the help of physical properties of methyl esters like density, compressibility and viscosity [14,17,20]. The calorific values of Mahua and pungamia methyl esters and their blends are lower than that of neat diesel due to their oxygen content. The existence of oxygen in the methyl esters helps for complete combustion of fuel. The maximum HRR of methyl ester and their blends is higher than that of neat diesel, particularly, 105.69kJ/m$^3$deg for PME20, 107.09kJ/m$^3$deg for MME20, 79kJ/m$^3$deg for PME40 and 86.47kJ/m$^3$deg for MME40 compared with 108.01kJ/m$^3$deg for neat diesel fuel. This is due to, as a result of the premix combustion phase and the shorter ignition delay for methyl ester blends.

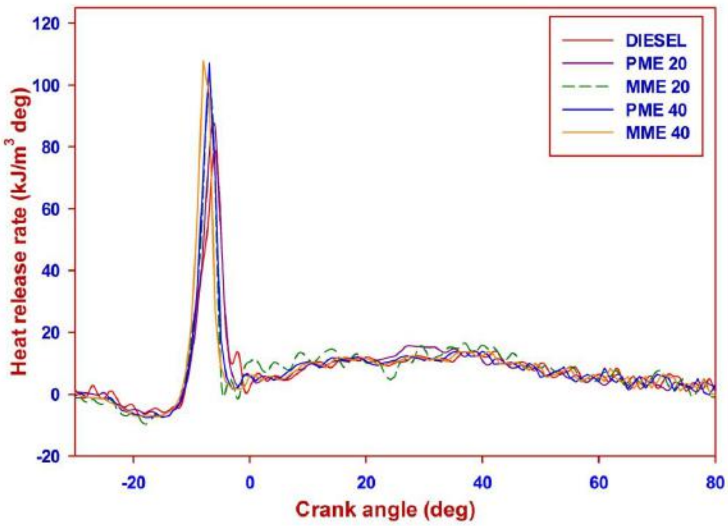


*Fig.11: Heat release rate against crank angle*

## V. CONCLUSION

From the experiments on the CRDI diesel engine fueled with Mahua and pongamia methyl esters blends, and neat diesel, the following conclusions can be drawn:

- Improvement in brake thermal efficiency was observed with Mahua methyl ester (MME40) by about 1.31% at optimized operating condition.
- With the use of methyl ester blends, the level of risky pollutants in the exhaust gas, such as HC, CO and smoke, was appreciably reduced when compared to that of diesel fuel.
- Mahua methyl ester blend (MME40) reduces CO emission up to 12.28% compared with neat diesel, because of methyl ester blends act as an oxygen buffer and exploit oxygen during the combustion of fuel.
- The smoke density of diesel engine was decreased on both MME and PME blends by about 3.44 – 5.02%, especially at full load.
- Methyl esters blended diesel fuel showed higher heat release rate and cylinder gas pressure at optimized operating conditions.

Hence, MME40 and PME40 reduces HC, CO and smoke emissions but in the case of NOx, they are not efficient, but MME20 is efficient in improving performance and produce less amount of NOx from the diesel engine, compared with other methyl ester blends.

## ACKNOWLEDGEMENT

The authors have no support or funding to report.

## CONFLICT OF INTEREST

This article is original and contains unpublished material. The corresponding author confirms that the other author has read and approved the manuscript and no ethical issues involved.

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