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Effect of pongamia biodiesel on emission and combustion characteristics of DI compression ignition engine

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Combustion

Abstract Biodiesel produced from pongamia oil has been considered as promising option for diesel engines because of its environmental friendliness. In this work, bio-diesel from pongamia oil is prepared (PME 100), tested on a diesel engine for different blends such as PME 20, PME 40, PME 60 and PME 80. Comparison is made with diesel operation. Parameters such as brake thermal efficiency, brake specific fuel consumption, carbon monoxide, unburned hydrocarbons, smoke and NO_x emissions are evaluated. Even though the performance reduces slightly when the engine is fueled with biodiesel, significant changes in the combustion parameters observed in case of biodiesel blends are significant to note. On the other hand, reduction in CO, HC and smoke is observed. Study reveals the effect of bio-diesel on a DI engine when compared to diesel and evolves conclusions with respect to performance and emissions.

1. Introduction

Energy is the most fundamental requirement for human existence. Consumption of fossil fuels has highly increased and the use of these energy resources has major environmental impact as well. Diesel fuel is largely used in transport, agriculture, commercial, domestic and industrial sectors for the generation of mechanical energy and electricity. Out of all the alternative fuels available, bio-diesel obtained from vegetable oils and animal fatty acids promises to be more eco-friendly when compared to diesel fuel [1]. Finding suitable sustainable fuel alternatives has become a high priority for many countries. Also, it will play major role in various industries in the near future. Bio-diesel is one of these sustainable fuels that is a non-petroleum based, consisting of alkyl esters derived from either transesterification of triglycerides obtained from vegetable oils or esterification of free fatty acids from animal fats with short-chained alcohols. It has many advantages that include low emissions, biodegradable, non-toxic and better lubricity. Even then, bio-diesel has not become a better alternative fuel that can be made commercially available, because of its higher production cost and non-availability of raw material. Poor oxidation stability of biodiesel is also one of the

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Nomenclature

ATDC	after top dead center	ppm	parts per million
BSFC	brake specific fuel consumption	PME	pongamia oil methyl ester
SEC	specific energy consumption	PME 20	20% PME and 80% diesel
BTE	brake thermal efficiency	PME 40	40% PME and 60% diesel
CO	carbon monoxide	PME 60	60% PME and 40% diesel
DI	direct injection	PME 80	80% PME and 20% diesel
UBHC	unburned hydrocarbon	PME 100	100% PME
NO_x	nitrogen oxide		

most serious restrictions in its commercialization and frequent use in DI engines [2]. One of the means to address these issues is by carrying out research and development in the field of oxidation stability of biodiesel and to see that cost of the biodiesel is reduced [3]. Another option for cost reduction is to produce biodiesel from waste fats that reduces the cost of processing through optimizing the variables that affect the yield and purity of biodiesel [4].

Numerous studies have been conducted on biodiesel in the past few decades. Several production methods have been reported that include blending of oils, microemulsion, pyrolysis and transesterification [5]. Transesterification is the general term used to describe the important class of organic reactions, where an ester is transformed into another by interchange of the alkoxy radical group. Transesterification involves stripping of glycerin from fatty acids with a catalyst such as sodium or potassium hydroxide and replacing it with an anhydrous alcohol that is usually methanol. However potassium hydroxide is considered as a best catalyst for transesterification of all types of vegetable oils. The resulting raw product is then centrifuged and washed with water to make it free from impurities. This yields methyl or ethyl ester (biodiesel) as well as small amount of glycerol, a valuable by-product used in making soaps, cosmetics and numerous other products. There are four transesterification processes for the formation of biodiesel from oils and fats. (i) Base-catalyzed transesterification. (ii) Direct acid-catalyzed transesterification. (iii) Enzyme catalytic conversion of the oil into fatty acids and then into biodiesel. (iv) Non-catalytic transesterification using methanol or methanol/co-solvent [6–9]. Out of these, base-catalyzed transesterification of vegetable oils with simple alcohol has long been the preferred method for producing biodiesel. Methanol is the most commonly used alcohol because of its low cost.

Large numbers of experiments have been conducted with different biodiesels prepared from various feedstocks on compression ignition engine under different operating conditions by researchers. Ejaz and Jamal [10] have significantly reviewed the results of engine tests carried out by earlier researchers using vegetable oil based fuels. Most of them have utilized sunflower oil, rapeseed oil, cottonseed oil, soybean oil, palm oil and peanut oil as fuel for diesel engines in different modes. They concluded that coking is a major problem for unmodified vegetable oils in diesel engine. But, the chemically processed biodiesel blends with diesel can be used successfully in a diesel engine for longer duration. Ramadhas et al. [11] have listed the advantages, challenges and technical difficulties of using vegetable oil based fuels in diesel engines. It was reported that the feedstock price of vegetable oils, homogeneity and material compatibility are the major challenges. Engine durability, popularization of environmental benefits of vegetable oils, and effects of glycerol on engine life are the primary technical difficulties of biodiesel. Almeida and Al-Shyoukh [12] held investigations on a diesel generator with preheated palm oil for different temperatures. Reduced NO_x emissions and increased CO, HC, and CO_2 emissions were obtained. Engine tests have been carried out by Devan and Mahalakshmi [13] with the aim of obtaining performance, emission and combustion characteristics of a diesel engine running on Methyl Ester of Paradise Oil (MEPS) and its diesel blends. Significant reduction in smoke and unburned hydrocarbon emissions by 40% and 27% for MEPS 100 was found. However, there was an increase of NO_x emission by 8% for MEPS 100. Suryanarayanan et al. [14] analyzed the performance and emission characteristics of methyl esters of Sunflower oil, Palm oil, Pungam oil, Jatropha oil, Rice bran oil and Waste cooking oil and compared with those of diesel. It is found that Sunflower oil Methyl Ester (SUME) has the highest brake thermal efficiency across the range of loads while Palm oil Methyl Ester (PAME) has the lowest specific fuel consumption among the biodiesels. On the other hand, NO_x emissions are found to be highest for SUME. All biodiesels record lesser CO, HC and soot emissions compared to diesel. Murugesan et al. [15] studied the prospects and opportunities of introducing vegetable oils and their derivatives as fuel in diesel engines. They had also discussed about peak pressure development, heat release rate analysis and vibration analysis of the engine in relation to the use of bio-diesel and conventional diesel fuel. Use of biodiesel in a conventional diesel engine results in substantial reduction in unburned hydrocarbon (UBHC), carbon monoxide (CO), particulate matters (PM) emission and oxide of nitrogen. Also, issues like on timing for diesel engine operation with vegetable oils and their blends and environmental considerations were discussed.

Reed et al. [16] converted waste cooking oil into its methyl and ethyl esters, and tested different blends of diesel and compared with neat biodiesel. It was reported that no significant difference occurred in the engine performance. Many researchers have also found slight increase in nitrogen oxide (NO_x) emissions and few others found slight increase in aldehyde emissions [13–17]. Murillo et al. [18] found increased NO_x emissions for a 3.5% increase in fuel density. It was also found that the number of double bonds, quantified as iodine number, correlated with NO_x emissions. In this context, the primary objective of this paper was to examine the potential of pongamia oil for its suitability as feedstock in biodiesel preparation and to compare the fuel properties of the methyl esters of pongamia oil (PME) with that of base line diesel fuel. Also, it is aimed to investigate the performance, combustion and emissions aspect of the DI diesel engine running on this biodiesel.

2. Material and methods

2.1. Fuel production and properties

The biodiesel fuel used in this study (methyl ester) is obtained from pongamia oil by transesterification process. It is the process by which fatty acid is converted into its corresponding ester. The mixture of pongamia oil, methanol (molar ratio of 6:1) and sodium hydroxide (NaOH) (1% w/w) as catalyst is taken in the reaction chamber fitted with condenser and thermometer. The entire mixture is heated at a temperature of 65 °C for 2 h and then cooled down to room temperature. After cooling, two layers are observed with top layer identified as methyl ester and bottom layer as since it has more density. Then the top layer is washed with distilled water and drained out. Finally, pongamia oil methyl ester (PME) is obtained as product and is used in the present study.

Numbers of tests are conducted to analyze the composition and physical–chemical properties of biodiesel in a certified laboratory. PME20, PME40, PME60, PME80 and PME100 represent various volumetric biodiesel quantities in the test fuel (biodiesel–diesel blend). Properties of all the test fuels are presented Table 1. It is comprehended that the physicochemical properties of biodiesel differ from that of conventional diesel; which could affect the diesel engine performance and emission characteristics without any further modification required to be done on the engine. The lower heating value of all biodiesel blends is decreasing with increasing biodiesel concentration in the blends. The heating value of PME100 is 23% lower than conventional petroleum diesel. Therefore, in order to generate the same power output, more fuel should be consumed for PME100. The acid value and flash point of biodiesel blends are higher than that of diesel. Flash point of biodiesel is 175 °C, which is higher than diesel. Even all the biodiesel blends have flash points much above that of diesel fuel indicating that biodiesel is safer than diesel fuel.

2.2. Experimental set-up

Experimental investigation is carried out on a typical single cylinder, four stroke, constant speed air cooled diesel engine. Schematic arrangement of the experimental setup is shown in Fig. 1. Engine is coupled with an air cooled eddy current dynamometer along with load cell. Load on the engine is varied with the help of the controller provided on the dynamometer. Standard burette apparatus along with stop watch is used for fuel flow measurement on volumetric basis. Exhaust gas temperature is measured using K-type thermocouple. Exhaust gas emissions such as CO, UBHC, CO_2, O_2, NO_x and excess air ratio are measured by using HORIBA MEXA 584L exhaust gas analyzer. AVL 437C Smoke meter is used to measure smoke opacity. Engine is started under no load condition and then warmed up at the rated speed of 1500 rpm and all the readings are taken under steady state conditions. Technical details of the engine are given in Table 2. Kistler pressure sensor 6613 CQ09 and Kistler 601A crank angle encoder with AVL INDIMICRA BW9871 software are used for combustion analysis. The experiments are carried out with fixed injection timing of 23° bTDC at an injection pressure of 200 bar. Engine performance parameters such as brake power, efficiency, emissions and smoke opacity are quantified. Engine is run at 1500 rpm and data are collected with respect to combustion, emission and performance parameters at various loads of 0%, 25%, 50%, 75% and 100%.

3. Results and discussions

Diesel engine performance, emission and combustion characteristics are analyzed for all blends of PME 20, PME 40, PME 60. PME 80 and PME 100 fuels and compared with petroleum diesel. All the performance and emission results are presented and discussed in this section.

3.1. Performance characteristics

3.1.1. Brake specific fuel consumption

The brake specific fuel consumption (BSFC) is the actual mass of fuel consumed to produce 1 kW power output in an hour. The variation in BSFC of diesel and all biodiesel blends is shown in Fig. 2. It is noted that BSFC of all the blends of PME 20, PME 40, PME 60, PME 80 and PME 100 is higher than that of petroleum diesel at various loading conditions. The percentage of pongamia biodiesel in blends influences the engine economy with better performance. It is found that the BSFC of PME 100, PME 80, PME 60, PME 40, PME 20 and petroleum diesel is 53.3%, 41.9%, 26.3%, 22.96%

Table 1 Properties of fuels.

Properties	Diesel	PME20	PME40	PME60	PME80	PME100
Acid number (mg of KOH/g)	Nil	0.033	1.41	1.53	> 1.53	> 1.53
Ash (% by mass)	Nil	0.021	0.028	0.035	0.053	0.085
Pour point (°C)	< −3	−3	−2	−2	−2	−1
Distillation (a) at 350 °C	84	75	75	59	32	31
(b) At 370 °C	93	90	90	80	48	46
Flash point, °C	53	56	56	60	80	175
Kinematic viscosity at 40 °C (CSt)	2.30	2.85	3.22	6.37	8.35	10.29
Moisture content (% by volume)	Nil	0.1	0.2	0.2	0.2	0.4
Density at 15 °C (kg/m^3)	824	844	852	875	889	912
Lower heating value (kJ/kg)	44,450	41,200	39,100	38,000	35,700	34,220
Oxidation stability at 110 °C, h [19]	–	–	–	–	–	2.3–11.6

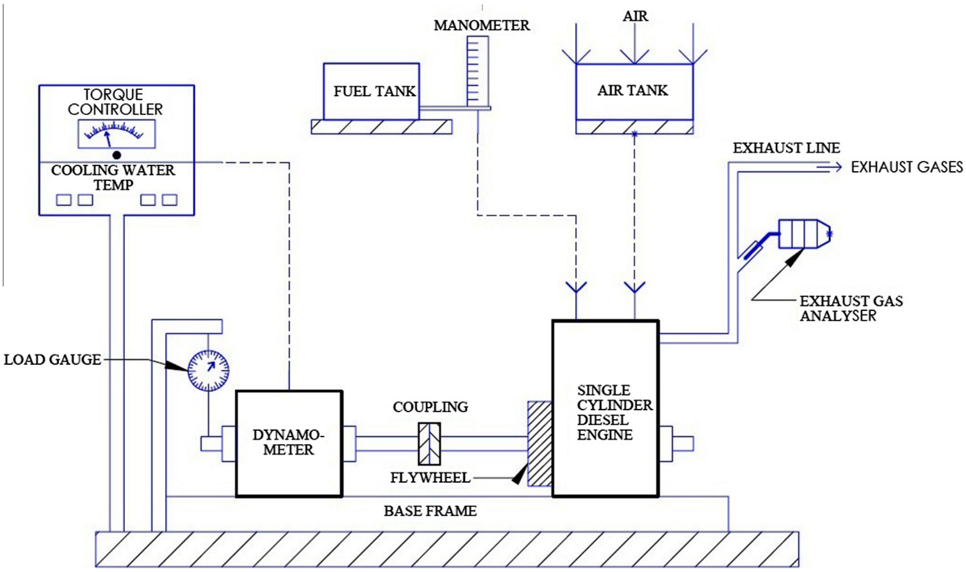

Figure 1 Schematic diagram of the experimental set up.

Table 2 Test engine specifications.

Make	Kirloskar
Model	TAF-1
Type	Single cylinder, naturally aspiration Four stroke, vertical
Ignition	Compression ignition
Fueling	Direct injection (DI)
Engine capacity	661 cm^3
Bore	87.5 mm
Stroke	110 mm
Compression ratio	17.5:1
Rated power	4.4 kW @ 1500 rpm
Injection timing	23° bTDC
Injection pressure	200 bar
Cooling system	Air cooling
Lubricating oil	SAE20W 40 (K-Oil)

and 11.1% higher than that of diesel respectively. This is due to the influence of lower heating value, higher density and viscosity of biodiesel when compared to diesel. Similar trends were reported earlier [20–21].

3.1.2. Specific energy consumption

Specific Energy Consumption (SEC) is the best parameter to compare the economy performance of an engine because of different heating values of biodiesel blends. SEC of various biodiesel blends and petroleum diesel is plotted in Fig. 3. SEC of all the tested fuels is found to be decreasing with increase in power output. The BSEC of PME 20, PME 40, PME 60, PME 80 and PME 100 is close to that of diesel at full load conditions. This may be attributed to lower heating value, higher density and viscosities of biodiesel when compared to diesel.

3.1.3. Brake thermal efficiency

Brake Thermal Efficiency (BTE), commonly known as fuel conversion efficiency that replicates the percentage of fuel

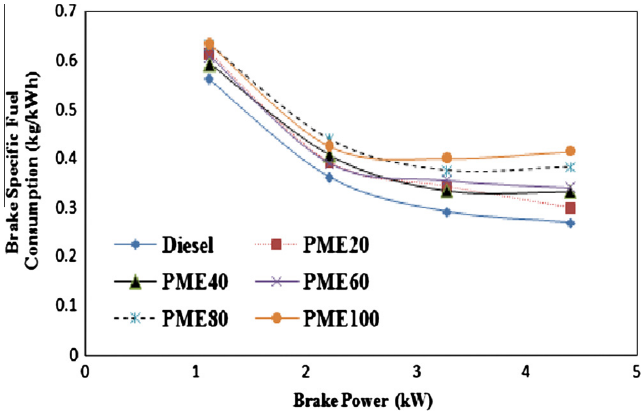

Figure 2 Variation in brake specific fuel consumption with brake power.

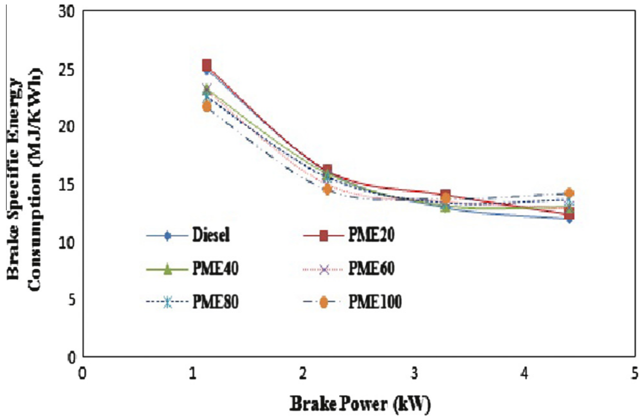

Figure 3 Comparison of specific energy consumption with brake power.

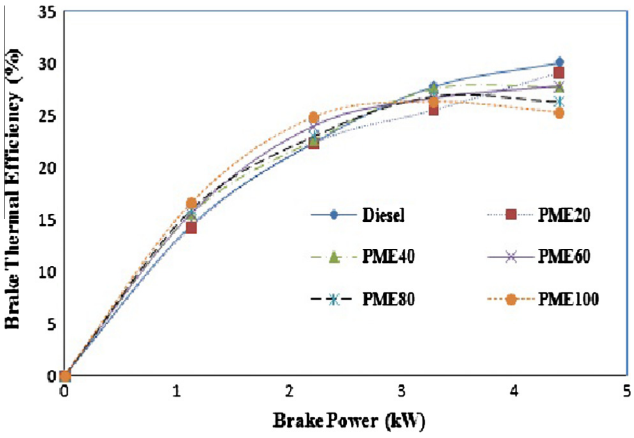

Figure 4 Brake thermal efficiency vs. brake power.

energy converted into useful energy. If different fuels are to be compared for the same engine, brake thermal efficiency is the most suitable parameter instead of specific fuel consumption. Fig. 4 shows the BTE of all biodiesel blends and petroleum diesel under different loading conditions. The maximum brake thermal efficiencies at full load condition for diesel, PME 20, PME 40, PME 60, PME 80 and PME 100 are calculated as 30.03%, 29.1%, 27.74%, 27.78%, 26.34% and 25.37%. It can be observed that the brake thermal efficiency of pongamia biodiesel is 15.5% lower than that of petroleum diesel at rated load. The lower decreasing trend for biodiesel blends was also presented in [22–24]. The lower BTE of biodiesel is greatly influenced by its BSFC and heating value.

3.2. *Emission characteristics*

3.2.1. *Unburned hydrocarbon emissions*

Unburned hydrocarbon (UBHC) pollutants are formed when the fuel is not completely burned. UBHC is one of the important parameters for determining the emission behavior of diesel engine. Comparison of UBHC of all the PME blends and diesel at various brake power is shown in Fig. 5. It is shown that the variation in UBHC decreases with the influence of PME percentage in bio-diesel blends. It is also confirmed that PME 100 reduced 45% of UBHC emissions when compared to base line diesel at full load condition. It is observed that UBHC reduction is due to the presence of oxygen content in the biodiesel that leads to faster the combustion chemical reaction [25].

3.2.2. *Carbon monoxide emissions*

Carbon monoxide (CO) is the most common type of fatal air poisoning in many countries. It is colorless, odorless and tasteless, but highly toxic gas. Fig. 6 shows the variation in carbon monoxide of all the tested fuels with respect to brake power. It is learned that the variation in CO emissions for all biodiesel blends and diesel is fairly small. It is also identified that CO concentration of PME 20 and PME 100 is 67% and 19% lower than conventional diesel at rated load. This may be due to the oxygen content and less C/H ratio of biodiesel that causes complete combustion. However, it is revealed that the decreasing trend of CO emission does not rely on biodiesel percentage in the blends [26].

3.2.3. *Oxides of nitrogen emissions*

NO_x emission is a generic term of nitric oxide (NO) and nitrogen dioxide (NO_2), which is produced from the reaction of nitrogen and oxygen gases in the air during combustion process. The maximum burned gas temperature, the relative concentration of oxygen and the reaction time are the critical variables for NO_x formation. The variation in NO_x concentration with brake power for PME 20, PME 40, PME 60, PME 80, PME 100 and petroleum diesel is plotted in Fig. 7. NO_x emissions of all biodiesel blends are higher than that of conventional diesel. It is found that NO_x emission of PME 100 is increased by 26% when compared to diesel at rated load and hike in NO_x emission is greatly influenced by the percentage of biodiesel in blends. Similar conclusion related to NO_x formation was obtained by Mazumdar and Agarwal [27]. The high combustion temperature and the presence of extra oxygen are the main parameters for more NO_x emissions. This can be reduced with proper adjustment of injection timing and recirculating the small portion of exhaust gas with fresh air during the induction process [28].

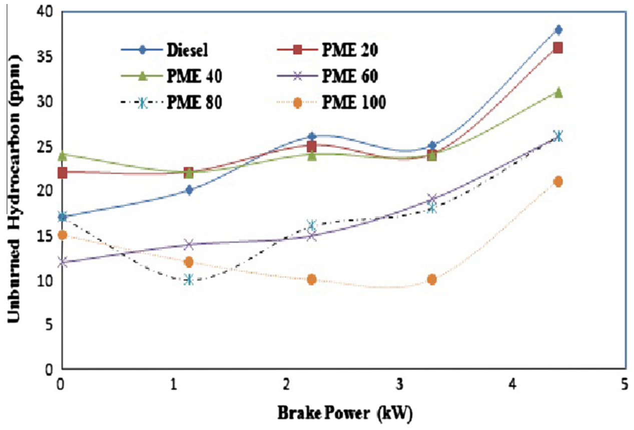

Figure 5 Variation in unburned hydrocarbon emission with brake power.

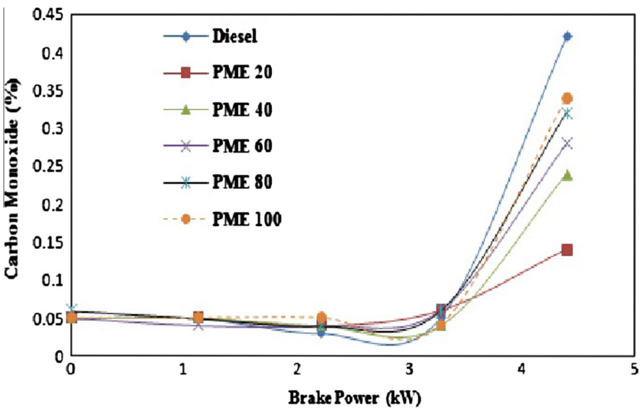

Figure 6 Variation in carbon monoxide emission with brake power.

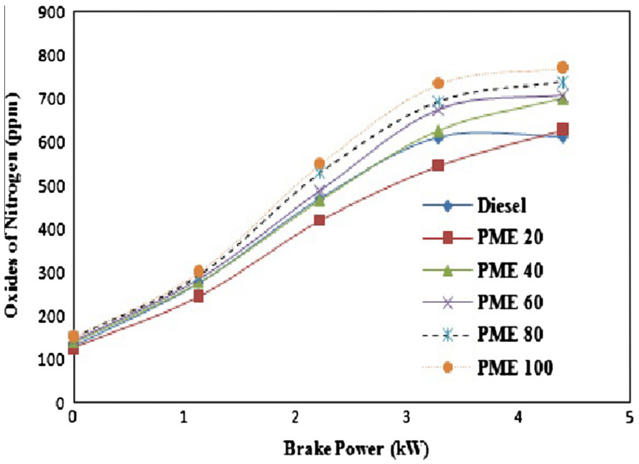

Figure 7 Variation in oxides of nitrogen with brake power.

3.2.4. Smoke opacity

Smoke is the visible product of diesel engine emission. The comparison of smoke opacity of PME 20, PME 40, PME 60, PME 80, PME 100 and petroleum diesel with respect to brake power is shown in Fig. 8. From the plot, it is observed that smoke opacity of biodiesel and its blends are significantly higher than that of petroleum diesel at part load conditions. But, as the load increases to maximum level, smoke opacity is effectively reduced up to 50% for PME and its blends with diesel. The formation of local rich mixtures in the combustion chamber due to high viscosity of biodiesel results in poor atomization at part load operations. At rated loads, the smoke formation is diminished because of oxygenated nature of biodiesel that leads to complete combustion [27,29,30].

3.3. Combustion characteristics

The combustion mechanism is one of the complicated phenomena in an I.C. engine. The characteristics of the combustion process are illustrated by using cylinder gas pressure, ignition delay period, combustion durations, intensity and heat release rate. These parameters can be calculated based on the cylinder pressure data variation that are received from the engine.

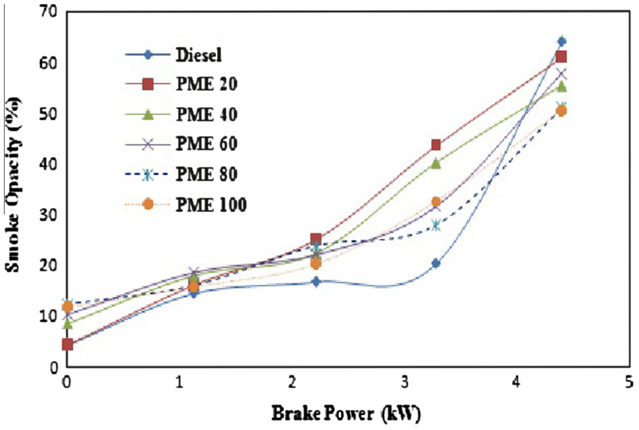

Figure 8 Variation in smoke opacity with brake power.

3.3.1. In cylinder pressure

In cylinder pressure measurement is the most important tool for understanding the combustion process. It is used to give sufficient information for the combustion analysis and to determine the heat release rate, mass fraction burned and cylinder pressure–volume etc. The variation in cylinder pressure with crank angle for PME 20, PME 40, PME 60, PME 80, PME 100 and petroleum diesel is shown in Figs. 9a–d. It can be observed that cylinder pressure of biodiesel blends with diesel follows similar trend as that of the conventional fuel under various operating conditions. Fig. 10 shows maximum cylinder pressure for various biodiesel blends at different engine loads. It is also revealed that as load increases, maximum cylinder pressure increases for all the tested fuels. Maximum cylinder pressure is almost identical for PME 40, PME 60, PME 80 and PME 100 when compared to diesel. But, the peak pressure for PME 20 is slightly higher by 2–3% than the rest of the tested fuels.

The peak pressure crank angle for biodiesel blends is plotted in Fig. 11. It can be noted from the figure that peak cylinder pressure occurs closer to TDC for all biodiesel blends and diesel fuels at low load operations. As the load increases, the peak cylinder pressure occurs relatively later for all fuels. This is due to the prolonged ignition delay period which extends the premixed combustion phase up to 10–12° aTDC.

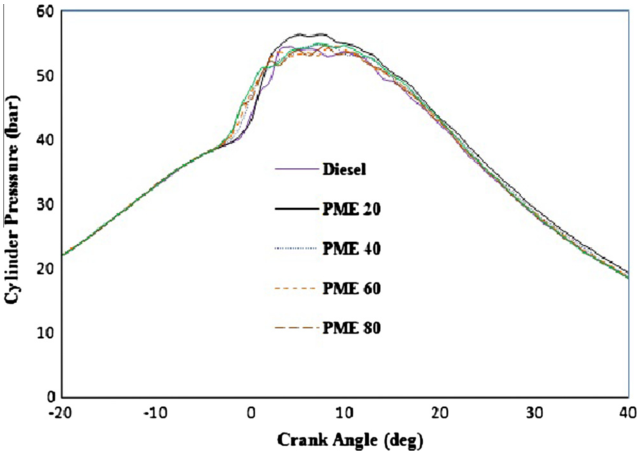

Figure 9a Cylinder pressure vs. crank angle at 25% load.

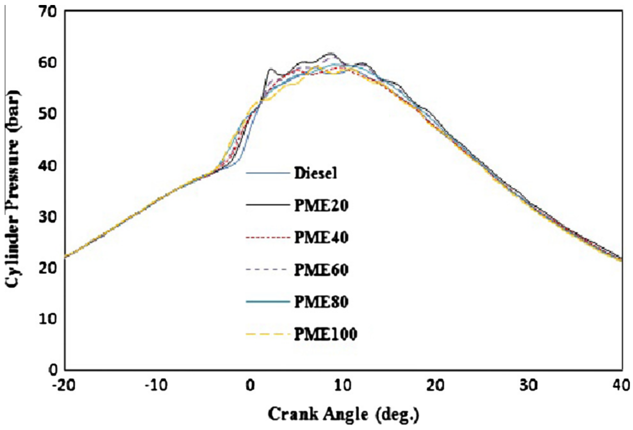

Figure 9b Cylinder pressure vs. crank angle at 50% load.

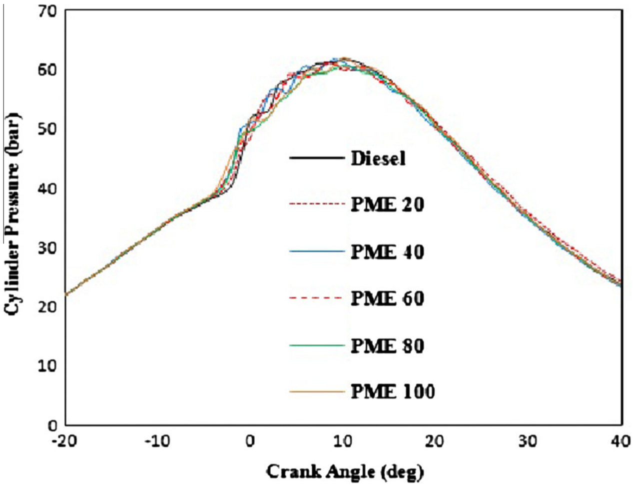

Figure 9c Cylinder pressure vs. crank angle at 75% load.

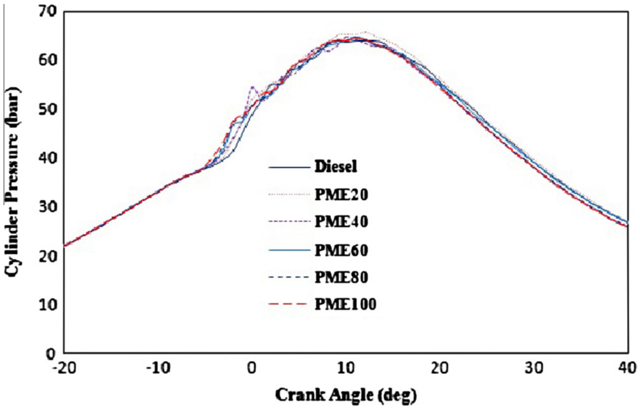

Figure 9d Cylinder pressure vs. crank angle at 100% load.

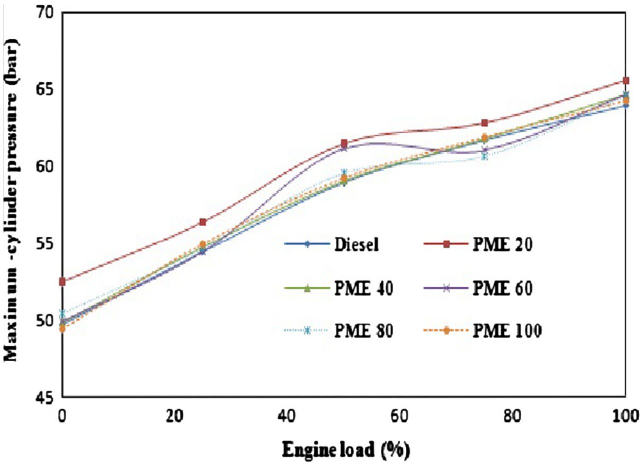

Figure 10 Maximum cylinder pressure for different fuels.

3.3.2. Heat release rate

Heat release rate is the rate at which the chemical energy of the fuel released by the combustion process in compression ignition engine. The direct injection diesel engine combustion process is divided into premixed phase and diffusion phase. It is calculated based on the first law of thermodynamics [28].

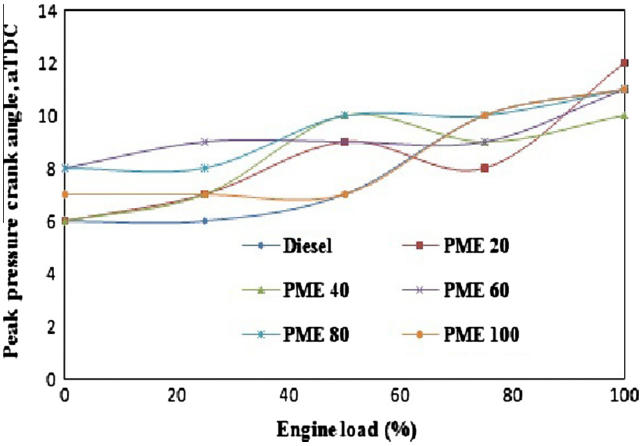

Figure 11 Peak pressure crank angle for biodiesel blends at various loads.

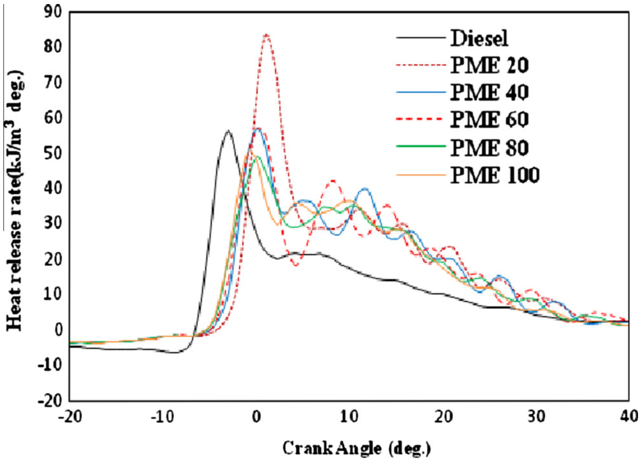

Figure 12a Heat release rate for diesel, biodiesel and their blends at 25% load.

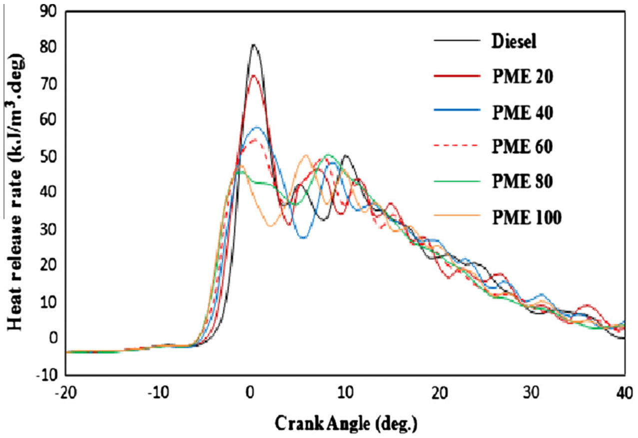

Figure 12b Heat release rate for diesel, biodiesel and their blends at 50% load.

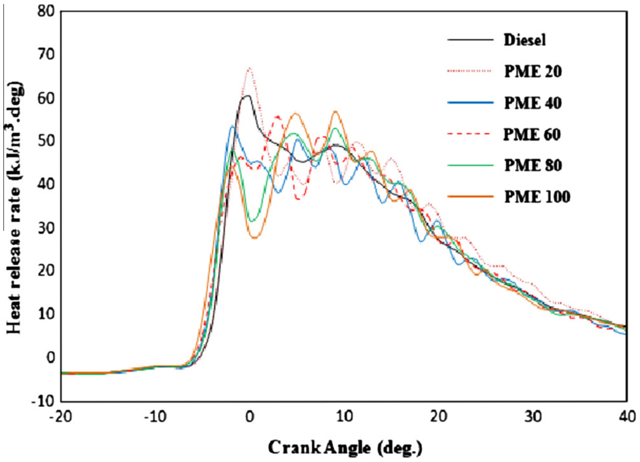

Figure 12c Heat release rate for diesel, biodiesel and their blends at 75% load.

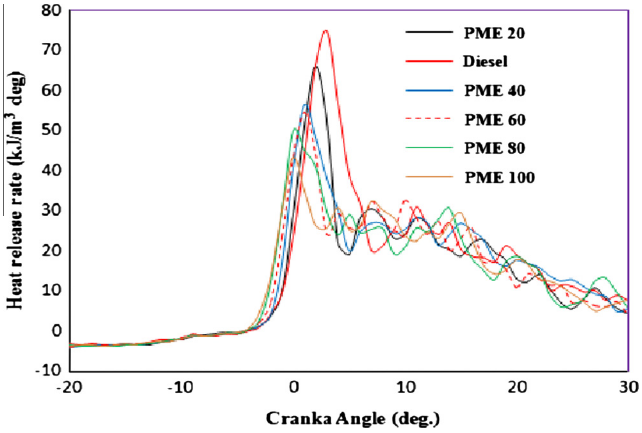

Figure 12d Heat release rate for diesel, biodiesel and their blends at 100% load.

Figs. 12a–d show the heat release variations for biodiesel and its blends at 25%, 50%, 75% and 100% load conditions. It can be seen that the maximum heat release rate of fuel is greatly influenced by the percentage of biodiesel in blends. It is also observed that combustion starts earlier for biodiesel and its blends. The peak heat release rate of biodiesel fuels is lower than conventional diesel fuel. This is due to the short delay period and lower calorific value of biodiesel that contributes to lower heat release rate. Similar results were reported earlier [27]. However, the heat release during diffusion (late) combustion phase for PME20, PME 40, PME 60, PME 80 and PME 100 is almost identical as diesel fuel. This is because of the excess oxygen content of biodiesel left over during earlier combustion stage continuing to burn in later stage.

4. Conclusion

The performance, emission and combustion characteristics of biodiesel derived from pongamia oil and its blends are compared with the conventional diesel fuel. Results are summarized as follows:

1. Diesel engine can perform satisfactorily with pongamia oil methyl esters and their blends without any engine modifications.
2. SFC increases with increase in percentage of biodiesel in the biodiesel blends because of the lower heating value of biodiesel.
3. It is also observed that there is significant reduction in CO, UBHC and smoke emissions for all biodiesel blends when compared to diesel fuel. However, NO_x emission of PME biodiesel is marginally higher than that of petroleum diesel.
4. The combustion analysis showed that the biodiesel added to the conventional diesel fuel decreased the delay period and lowered the heat release rate of the premixed combustion.

Thus, results indicate that pongamia oil methyl ester can be used as an alternative and environment friendly fuel for a diesel engine. However, detailed analysis of more blends will surely give an emphasis on the kind of bio-diesel that can be finally used in I.C. engines in the days to come in order to overcome the disadvantages of the petroleum diesel fuel that can be commercially developed as well.

References

[1] Cabakci M. The potential of restaurant waste lipids as biodiesel feedstock's. Bioresour Technol 2007;98(1):183–90.

[2] Rawat DS, Joshi G, Lamba BY, Tiwari AK, Mallick S. Impact of additives on storage stability of Karanja (Pongamia Pinnata) biodiesel blends with conventional diesel sold at retail outlets. Fuel 2014;120:30–7.

[3] Potgieter JH, Potgieter-Vermaak SS, Tona DD. A proposed alternative suggestion for the disposal of used cooking oil. J Appl Sci 2004;4(2):313–6.

[4] Riera JB, Rafael Sdony, Refecas M, Guardiola F. Recycled cooking oils: assessment of risks for public health, European Parliament. Directorate General for Research. The STOA Programme; 2000.

[5] Ma F, Hanna MA. Biodiesel production: a review. Bioresour Technol 1999;70(1):1–15.

[6] Demirbas A. Biodiesel from waste cooking oil via base–catalytic and supercritical methanol transesterification. Energy Convers Manage 2009;50(4):923–7.

[7] Antonlin G, Tinaut FV, Briceno Y, et al. Optimization of biodiesel production by sunflower oil transesterification. Bioresour Technol 2002;83(2):111–4.

[8] Han H, Cao W, Zhang J. Preparation of biodiesel from soybean ol using supercritical methanol and CO_2 as co-solvent. Proc Biochem 2005;40:3148–51.

[9] Singh ABH, Thompson J, Van Gerpen J. Process optimization of biodiesel production using different alkaline catalysts. Appl Eng Agric 2006;22(4):597–600.

[10] Shahid Ejaz M, Younis Jamal. A review of biodiesel as a vehicular fuel. Renew Sustain Energy Rev 2008;12(9):2484–94.

[11] Ramadhas AS, Jayaraj S, Muraleedharan C. Use of vegetable oils as I.C. engine fuels – a review. Renew Energy 2004;29(5):727–42.

[12] Al-Widyan ML, Al-Shyoukh AO. Experimental evaluation of the transesterification of waste palm oil into biodiesel. Bioresour Technol 2002;85(3):253–6.

[13] Devan PK, Mahalakshmi NV. Utilization of unattended methyl ester of paradise oil as fuel in diesel engine. Fuel 2009;88(10):1828–33.

[14] Suryanarayanan S, Janakiraman V, Rao G, Sampath S. Comparative study of the performance and emission characteristics of biodiesels from different vegetable oils with diesel. SAE Technical Paper series 2008-01-1581.

[15] Murugesan A, Umarani C, Subramanian R, Nedunchezhian N. Biodiesel as an alternative fuel for diesel engines – a review. Renew Sustain Energy Rev 2009;13(3):653–62.

[16] Reed TB, Graboski MS, Gaur S. Development and commercialization of oxygenated diesel fuels from waste vegetable oils. In: Proceedings of meeting of energy from biomass and wastes. Chicago: The Institute of Gas Technology, IIT Center; 1991. p. 907–14.

[17] Ozsezen AN, Canakci M, Turcan A, Sayin C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel 2009;88(4):629–36.

[18] Murillo S, Miguez JL, Porterio J, Granada E, Moran JC. Performance and exhaust emissions in the use of biodiesel in outboard diesel engines. Fuel 2007;86(12–13):1765–71.

[19] Dwivedi Gaurav, Sharma MP. Prospects of biodiesel from pongamia in India. Renew Sustain Energy Rev 2014;32:114–22.

[20] Dorado MP, Ballesteros E, Arnal JM, Gomez J, Lopez F. Exhaust emissions from a diesel engine fueled with transesterified waste olive oil. Fuel 2003;82(11):1311–5.

[21] Lapuerta M, Agudelo JR, Rodriguez- Fernandez J. Diesel particulate emissions from used cooking oil biodiesel. Bioresour Technol 2008;99(4):731–40.

[22] Nabi N, Rahman M, Akhter S. Biodiesel from cotton seed oil and its effect on engine performance and exhaust emissions. Appl Therm Eng 2009;29:2265–70.

[23] Sahoo PK, Das LM. Combustion analysis of Jatropha Karanja and Polanga based biodiesel as fuel in a diesel engine. Fuel 2009;88:994–9.

[24] Rao GLN, Sampath S, Rajagopal K. Experimental studies on the combustion and emission characteristics of a diesel engine fueled with used cooking oil methyl ester and its diesel blends. Int J Eng Appl Sci 2008;4:64–70.

[25] Deepak KA, Avinash AK. Performance and emission characteristics of Karanja oil (preheated blends) in a direct injection compression ignition engine. Appl Therm Eng 2007; 27(13):2314–23.

[26] Fujia Wu, Wang Jianxin, Chen Wenmiao, Shuai Shijin. A study on emission performance of a diesel engine fueled with five typical methyl ester biodiesels. Atmos Environ 2009;43(7):1481–5.

[27] Mazumdar B, Agarwal AK. Performance, emission and combustion characteristics of biodiesel (Waste cooking oil methyl ester) fueled IDI engine. SAE Technical series. 2008-01-1384.

[28] Heywood J. Internal combustion engine fundamentals. MaGraw-Hill; 1988.

[29] Sureshkumar K, Velraj R, Ganesan R. Performance and exhaust emission characteristics of a CI engine fueled with pongamia pinnata methyl ester (PPME) and its blends with diesel. Renew Energy 2008;33(10):2294–302.

[30] Nabi Nurun, Najmul Hoque SM, Shamim Akhter Md. Karanja (Pongamia Pinnata) biodiesel production in Bangladesh, characterization of karanja biodiesel and its effect on diesel emissions. Fuel Process Technol 2009;90:1080–6.

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