

Influence of Key Properties of Pongamia Biodiesel on Performance Combustion and Emission Characteristics of a DI Diesel Engine

CH. SATYANARAYANA¹, AND P. V. RAO²

¹Department of Marine Engineering, ²Department of Mechanical Engineering
Andhra University
Visakhapatnam-530 003, Andhra Pradesh
INDIA

prof.pvrao@gmail.com satyanarayanachaliki@gmail.com <http://www.andhrauniversity.info>

Abstract: The purpose of this study is to examine the influence of key properties of pongamia biodiesel on engine performance, combustion, and emission characteristics of direct injection diesel engine. The key properties of the pongamia biodiesel such as viscosity, density, bulk modulus, calorific value, iodine value, cetane number, saturation% and oxygen% are considered for this study. Experiments were conducted in a naturally aspirated, single cylinder, four-stroke, stationary, water cooled, constant rpm, in-line (pump-high pressure tube-fuel injector) direct injection diesel engine with pongamia biodiesel (with and without preheating), and petroleum diesel as fuels. The performance was evaluated in terms of fuel consumption, brake specific energy consumption, and thermal efficiency. A significant improvement in thermal efficiency was observed with preheated biodiesel. The peak pressures and peak heat release rates for biodiesel was slightly higher than diesel fuel. The high peak pressures of the biodiesel are probably due to dynamic injection advance caused by its higher bulk modulus. The higher values of peak heat release rates indicate better premixed combustion with the biodiesel. However, the peak pressures for preheated biodiesel decreases due to late injection and faster evaporation of the fuel. It was observed that at full load the nitric oxide emission of biodiesel is increased by 6 %. The hydrocarbon emissions of the biodiesel are very low and are reduced up to 32 % as compared to that of diesel fuel. There is a significant reduction in all exhaust gaseous emissions. Also a considerable reduction in nitric oxide emission is observed with preheated biodiesel due to change in premixed combustion phase. However when the preheated biodiesel is used, the smoke emission was increased due to prolonged combustion (diffusion) at lower viscosity. A considerable reduction in carbon monoxide emission was also observed with the preheated biodiesel.

Key-Words: Pongamia, properties, bulk modulus, preheating, DI diesel engine, combustion, emissions

1 Introduction

Recent fuel crisis [1], increasing cost, and shortage of petroleum diesel (PD) have stimulated the economic feasibility studies of vegetable oils as a fuel in diesel engines [2]. India has about 86 types of oilseed-bearing perennial trees [2, and 3] of which karanja seed (*Pongamia glabra*); mahua (*Madhuca Indica*), neem (*Azadirachta*) and jatropha (*jatropha curcas*) are the important ones.

2 Pongamia Oil

Pongamia, a medium sized glabrous tree, popularly known as karanja is widely available in India. The oil content of karanja seed is about 33 % [4]. Pongamia oil has a yellowish orange color. The feed stock dependent fatty acid compositions (hydrocarbon chains) of pongamia oil vary from

'C₁₆ to C₂₄', with the long chain oleic acid (C_{18:1}), linoleic acid (C_{18:2}), palmitic acid (C_{16:0}), stearic acid (C_{18:0}), and behenic acid (C_{22:0}) are the highest [4] as shown in Fig. 1 and 2. The amount of fatty acids present in pongamia oil is oleic acid: 49.4%, linoleic acid: 19%, palmitic acid: 10.6%, stearic acid: 6.8%, behenic acid: 5.3%. This pongamia oil contains 29.2% saturated fatty acids (SFA), 51.8% of mono-unsaturated fatty acids (MUFA) and 19% of poly-unsaturated fatty acids (PUFA) as shown in Fig. 3.

The carbon chain of PD fuel includes both medium (C₈-C₁₂) and long (C₁₄-C₃₂) carbon chain. The hydrocarbons in PD fuel range in size from 8 carbon atoms per molecule to 32 carbon atoms per molecule (C₈-C₃₂) [5]. The peak in the carbon-number distribution occurs at about 13 to 19 carbon atoms per molecule (C₁₃-C₁₉), as shown in Fig. 1.

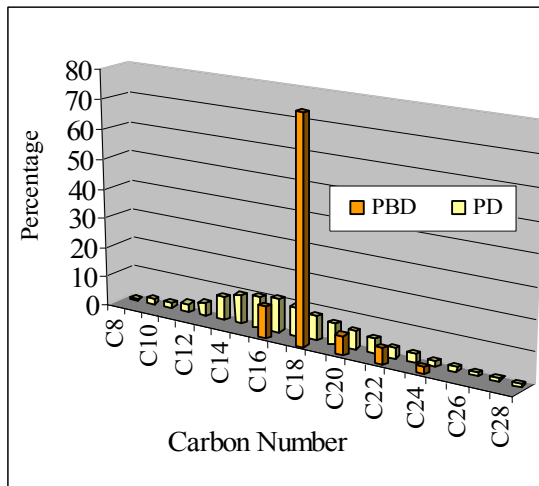


Fig. 1: Carbon number distribution

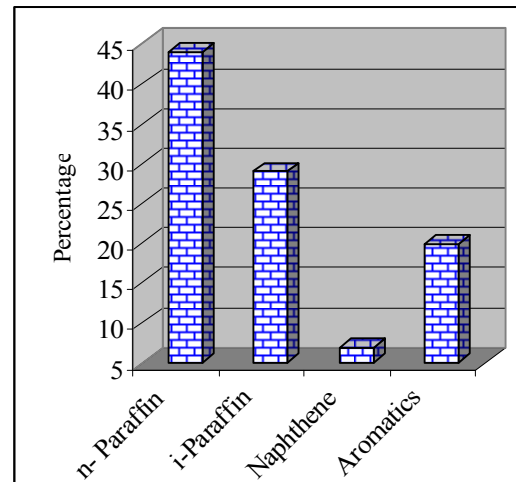


Fig. 4: Composition of PD

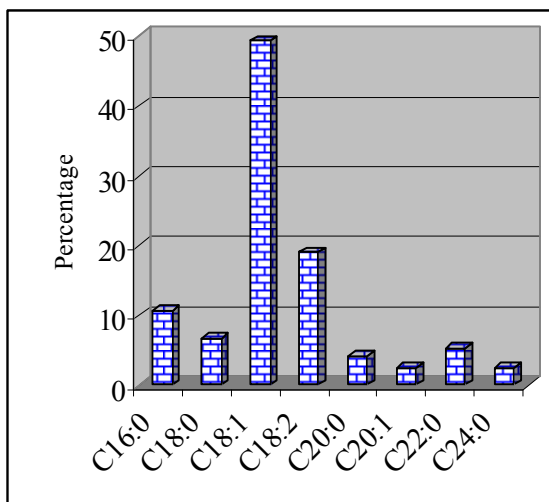


Fig. 2: Fatty acids in pongamia oil

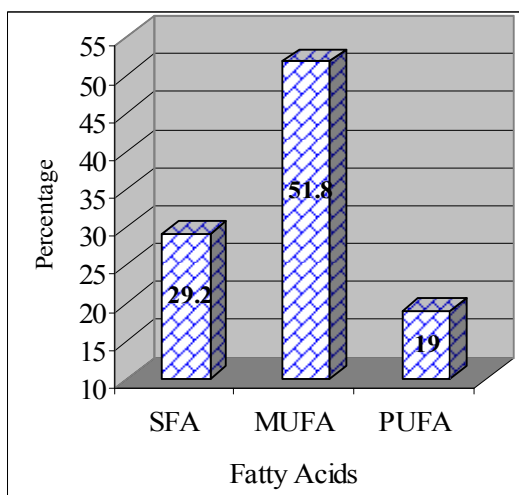


Fig. 3: Saturated and unsaturated fatty acids in pongamia oil

PD fuel typically contains over 400 distinct types of organic compounds. Approximately 80 % (vol.) of the PD fuel contains alkanes, with the remainder (i.e. 20%) comprised of aromatic molecules. Typical PD fuel contains approximately 44% of n-Paraffin, 29% of i-Paraffin and 7% of Naphthene as shown in Fig. 4. The aromatics include polycyclic aromatic compounds containing 2, 3, 4, and 5 fused benzene rings. The aromatics containing multiple benzene rings are known as poly-aromatic hydrocarbons (PAHs). The aromatic benzene rings of the polycyclic hydrocarbons act as nuclei for growth of undesired soot [6].

3 Biodiesel Preparation

The BD fuel is produced by chemically reacting the oil with an alcohol (methyl), in the presence of a catalyst. A two-stage process [7, 8, and 9] is used for the esterification of the pongamia oil. The first stage of the process is to reduce the free fatty acids (FFA) content in pongamia oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid-98% pure) in one hour time of reaction at 55 °C. In the second stage, the triglyceride portion of the pongamia oil reacts with methanol and base catalyst (sodium hydroxide-99% pure), in one hour time of reaction at 65 °C, to form methyl ester and glycerol. The raw fatty acid methyl ester is then purified by the process of water washing with air-bubbling. The biodiesel produced from pongamia oil is known as pongamia oil methyl ester (POME) or simply known as pongamia biodiesel (PBD).

4 Biodiesel Characterization

Measurements of key properties (both physical and chemical) were carried out according to ASTM D6751-02 (Standard Specification for Biodiesel Fuel (B100) Blend Stock for Distillate Fuels [10]) standards. The specifications and manufacturers of the instruments were given in the following Table 1.

Table 1: ASTM methods and instruments used to measure various fuel properties.

Fuel Property	ASTM method	Instrument	Model
Density	D 1298	Hydrometer	Petroleum Instruments, India
Flash and Fire Points	D92	Cleveland Open-Cup Flash Tester	Petroleum Instruments, India
Calorific Value	D 240	Bomb Calorimeter	Parr, UK
Kinematic Viscosity	D 445	Kinematic Viscometer	Setavis, UK

From the testing of the pongamia biodiesel, it is observed that these properties are meeting the specifications of ASTM biodiesel standards as shown in Table 2, and PBD was found suitable for usage as biodiesel. The importances of biodiesel key properties are discussed as follows:

4.1 Oxygen and calorific value

The PD fuel made up of a mixture of various hydrocarbon molecules and contain little oxygen (up to 0.3%) and very small amount of sulfur, while the pongamia biodiesel consists of three basic elements namely: carbon, hydrogen and significant amount of oxygen (11%) as shown in Table 2. The increase of O₂ in biodiesel is related to the reduction of C and H₂, causes the lower value of lower calorific value (LCV) of the biodiesel as compared to that of PD fuel, because O₂ is ballast in fuel and 'C and H₂' are the sources of thermal energy. The calorific value is directly related to elemental composition of the fuel. The LCV of PBD is lower than PD fuel because of oxygen [11] and the biodiesel consists of esters of fatty acids with a different degree of saturation. The biodiesel has lower volumetric heating values (about 10%) than PD fuel. The stoichiometric air-fuel ratio of biodiesel will be lower than PD fuel because of O₂ is present in the biodiesel, as a result the

combustion efficiency of the BD fuel will be increased [12].

Table 2: Properties of test fuels in comparison to ASTM biodiesel standards.

Property	Fuel			ASTM Standards
	Units	PD (HC)	PBD (FAME)	Biodiesel D 6751-02
Carbon Chain	Cn	C ₈ -C ₂₈	C ₁₆ -C ₂₄	C ₁₂ -C ₂₂
Density (ρ)	gm/cc	0.825	0.875	0.87-0.89
Bulk Modulus (β) @ 20 MPa [13]	MPa	1475	1800	-----
Kinematic Viscosity @ 40 °C	cSt	2.25	4.2	1.9-6.0
Cetane Number	-----	48	55.84	48-70
Iodine Value	g Iodine/100 g	38	81	120 max. -----
Oxygen	%	0.3	11	11
Air/Fuel ratio (Stoichiometric)	-----	14.86	13.8	13.8
Lower Calorific Value	kJ/kg	42 500	38 300	37 518
Sulfur	%	0.25	0	0.05
Flash Point, (open cup)	°C	66	174	130 min.
Molecular weight		226	281	292
Color	-----	Light yellow	Yellowish orange	----

4.2 Cetane number

The ignition quality of the fuel is measured by cetane number (CN) and it measures how easily ignition occurs. The CN assists in smooth combustion with lower knocking characteristics in diesel engines. The CN requirement for the engine depends on the design, size, speed, and load. Diesel

engines that are run on low cetane fuels will suffer from excessive CO, HC, PM and smoke emissions, especially at low load and low temperature operations. The CN depends on fuel composition and influences the beginning of the process of combustion and emissions. Cetane number of biodiesel depends on fatty acids of feedstock [9]. The CN for PBD is 55.84 [4] and for PD is 48.

4.3 Iodine value

The iodine value (IV) shows the level of unsaturation of the fuel, which means, higher the percentage of unsaturation, larger will be the iodine value [14]. The PBD with 70.8% unsaturation (29.2% saturates) has an iodine value of 81; while the PD with 40% unsaturation (60% of saturates) has an iodine value of 38 as shown in Table 2.

4.4 Density and bulk modulus

The density (ρ) of biodiesel is more than that of PD fuel and this compensates their lower values of calorific value. For PBD, the density is lower than that of water and its viscosity is low enough to allow 'pump-ability'. The bulk modulus (β) of a liquid fuel is defined as the pressure required to produce unit volumetric strain and is given by the equation (1) [11, 15]. The ' β ' is a function of fuel temperature, pressure, and density. The velocity (s) of propagation of the pressure waves (or pulses) through the fuel discharge pipe is given by the equation (2) [16, 17, 18, and 19]. The values of ' β ' and ' ρ ' of PBD fuel is more than that of PD fuel as shown in Table 2.

$$\beta = \rho \cdot (\partial p / \partial \rho)_T \text{ ----- (1)}$$

$$s = c \cdot \sqrt{(\beta \cdot g / \rho)} \text{ ----- (2)}$$

Where ' c ' is velocity of sound and ' g ' is acceleration due to gravity

4.5 Flash point

The flash point temperature of PBD is higher than that of PD fuel as shown in Table 2. The higher value of flash point belongs to biodiesel, because the biodiesel do not have the light fractions. The safety of the biodiesel is ensured due to higher flash point temperature.

4.6 Kinematic viscosity

The kinematic viscosity (KV) influences the injection characteristics (spray pattern and depth of penetration) of the fuel, and the quality of filtering. Viscosity of the fuel decreases with the increase of temperature, which in turn decreases the emissions of non-combusted products. The viscosity of PD and PBD at 30 °C is 3.0, and 5.8 cSt respectively, as shown in Figure 5. The high viscosity of PBD reduces the leakage of fuel in the plunger and barrel pair (Fig. 6) of the fuel pump [20] and minimum viscosity limits are imposed to prevent the fuel from causing wear in the fuel injection pump. The viscosity of PBD at 50 °C is 3.0 cSt and is equal to that of PD fuel at engine room temperature of 30 °C, as shown in Fig. 5.

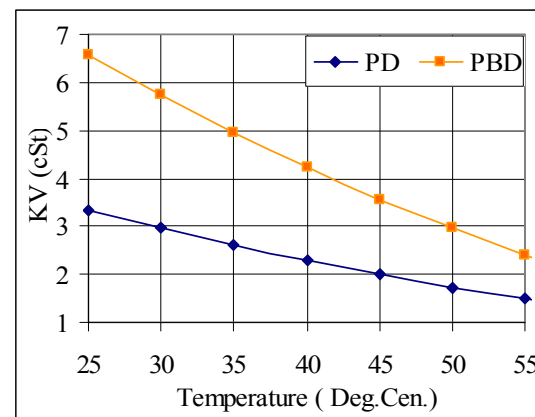


Fig. 5: Temperatures versus kinematic viscosity

5 Experimentation, Instrumentation and Procedure

The experiments were performed on a naturally aspirated, 4-stroke cycle, single cylinder, direct injection diesel engine, with the specifications shown in Table 3.

This engine employs the traditional, cam-driven, in-line fuel injection system (Fig. 6). It consists of a fuel pump (jerk pump), a high pressure tube (or fuel discharge tube) of length 585 mm (23 inch. approx.), and an injector (or atomizer). The pressure pulses (or waves) are generated by the pump plunger and the 'column of fuel' formed by the pump chamber, discharge tube, and the injector. This 'column of fuel' behaves like a stiff spring. The pressure pulses propagate through the 'column of fuel' to develop pressure at the nozzle end. When

the fuel pressure reached a pressure more than that required to open the needle valve of the injector, the needle valve is lifted to inject the fuel into the cylinder. For fuels with higher bulk modulus of compressibility, a more rapid transfer of the pressure wave takes place from pump end to the injector needle valve and the earlier needle valve lift causes an advanced (or early) injection. Therefore, the fuel that is less compressible, such as PBD, will inject prematurely in this system.

Table 3: Test engine specifications

Engine Make and Model	Kirloskar (India), AV1
Maximum Power Output	3.72 kW
Rated Speed (constant)	1500
Bore x Stroke	80 mm x 110 mm
Compression Ratio	16.5
Fuel Injection System	In-Line, Direct Injection
Nozzle Opening Pressure	205 bar
Method of Cooling	Water cooled
BMEP @1500 rpm	5.42 kg/cm ²

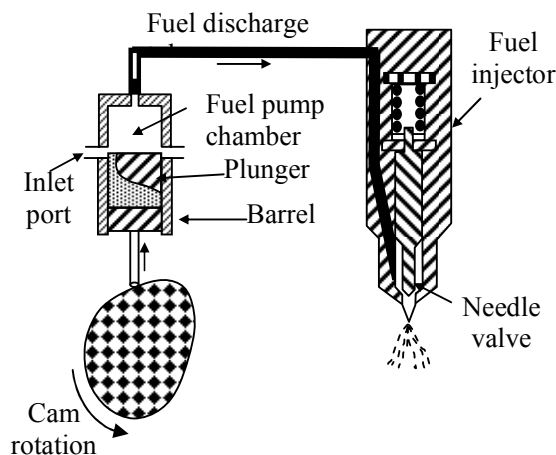


Fig. 6: Conventional, cam driven, in-line fuel injection system

The engine is tested with baseline PD fuel, and PBD. Engine is also tested with preheated PBD (PBD_H) to find the influence of reduced viscosity on performance, combustion, and emission characteristics. For preheating PBD fuels; heating

devices were placed along the fuel discharge tube. The fuel injection was performed at a static injection timing (optimum) of 23° BTDC set for PD fuel. The engine is allowed to warm up at constant speed of 1500 rpm, until the cooling water temperature reaches a steady state of 80 °C. Eddy current dynamometer is used to measure the power (or torque). Engine brake load was varied in five steps (at 0 kW, 0.93 kW, 1.86 kW, 2.79 kW, and 3.72 kW), ranging from 0% to 100% of the rated power output of 3.72 kW. Apex innovations, Pune, India, software: C7112 is used to record the in cylinder combustion pressure. Pressure signals were obtained using data acquisition system. The average pressure data from 20 consecutive cycles were used for calculating combustion pressure parameters.

6 Results and Discussion

6.1 Performance

The engine performance was evaluated in terms of fuel consumption (FC), brake thermal efficiency (BTE), and brake specific energy consumption (BSEC).

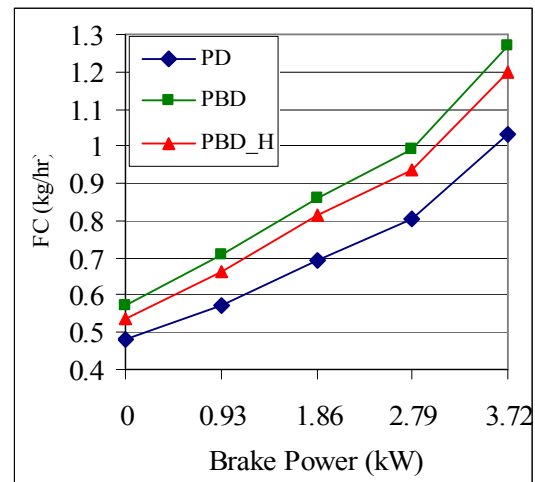


Fig. 7: Fuel consumption

6.1.1 Fuel consumption

The fuel consumption of PBD is more when compared to PD at all loads as shown in Fig. 7. At full load the FC for PD, PBD, and PBD_H are 1.03, 1.27 and 1.19 kg/hr respectively. PBD contains more oxygen (11%) and less number of hydrocarbons as compared to that of PD fuel. Therefore the lower calorific value (LCV) is less for

PBD than PD fuel. Consequently the FC is more for PBD than PD. It is also observed that fuel consumption is reduced at all loads for PBD_H when compared to PBD. This is due to improved spray characteristics and increased rate of fuel evaporation of PBD_H at preheated temperature of 50 °C.

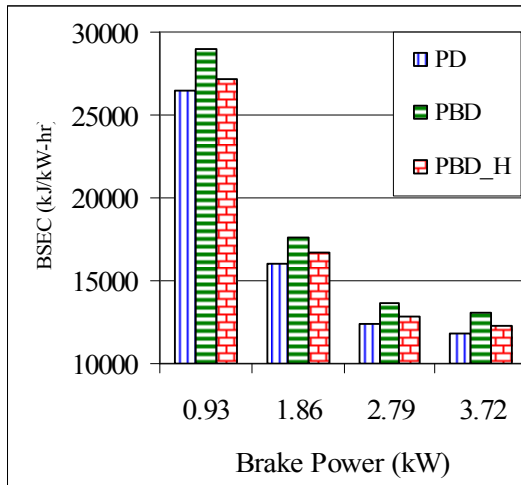


Fig. 8: Brake specific energy consumption

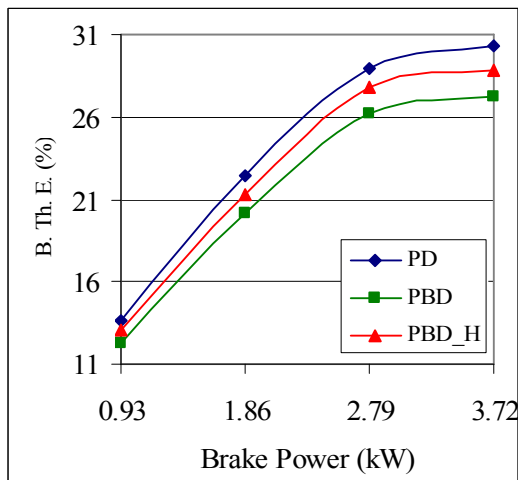


Fig. 9: Brake thermal efficiency

6.1.2 Brake specific energy consumption

Brake specific energy consumption (BSEC) is an ideal variable, because it is independent of the fuel. The BSEC is the input energy required to develop unit power output. Fig. 8 indicates the variation of BSEC with power output. BSEC of PBD is higher at all levels of power output compared to corresponding PD values. This is presumably due to

lower value of LCV and higher value of kinematic viscosity. Minimum BSEC of PBD and PBD_H are 13 060 kJ/kW-hr and 12 294 kJ/ kW-hr respectively, against 11 868 kJ/kW-hr of PD fuel. The decrease in BSEC of PBD_H may be attributed to increase in combustion efficiency with preheating of biodiesel.

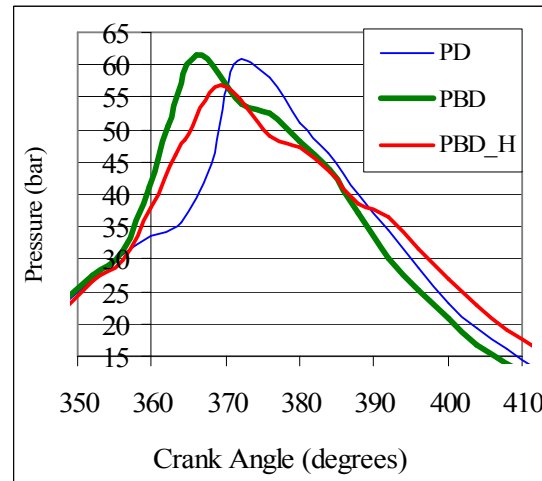


Fig. 10: Cylinder pressure

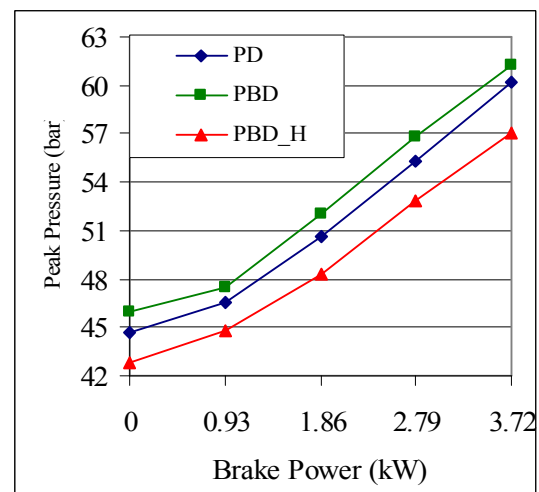


Fig. 11: Peak pressures

6.1.3 Brake thermal efficiency

The Fig. 9 shows the variation of brake thermal efficiency with power output. The brake thermal efficiency increases as the output power increases, for both the fuels. At full load, the efficiency of PD, PBD, and PBD_H are 30.3%, 27.2% and 28.8% respectively. According to thermodynamic analysis, the degree of constant volume combustion increases the indicated thermal efficiency. As shown in

Fig.10, the premixed combustion of PBD is very close to top dead center (TDC) and this behavior is due to early injection caused by the higher bulk modulus of PBD than that of PD fuel. The improvement in thermal efficiency of PBD_H is attributed to improved fuel spray characteristics, and faster evaporation of biodiesel.

Fig. 11 shows that the peak pressures of the PBD_H are less than those of PBD. When the engine is running on PBD_H, the injection is slightly delayed, due to decrease in bulk modulus of PBD with increasing fuel temperature. Therefore the reason for lower peak pressure attributed to early burning of PBD_H due to its faster evaporation at its preheated temperature (50°C), which leads to reduction in its ignition delay.

6.2 Combustion analysis

The combustion process in diesel engines is mainly divided into three phases as shown in Fig. 12.

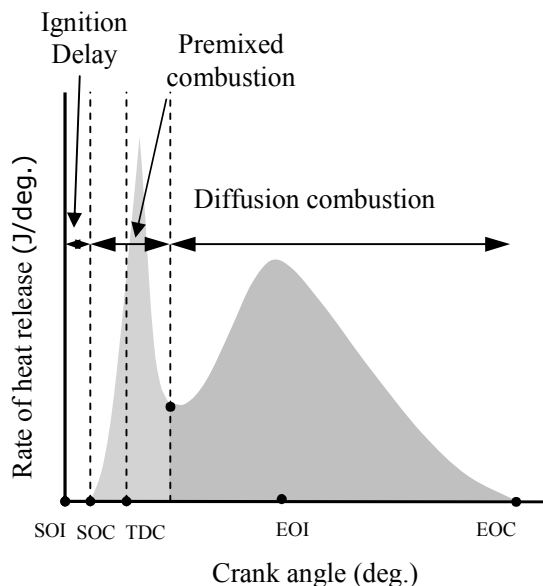


Fig. 12: Three phases of combustion

The first phase of combustion is called as ignition delay (ID), in which the tiny fuel droplets evaporates and mixes with high temperature (or high pressure) air. ID effects on rate of combustion. The delay period depends mainly on fuel cetane number (CN), and temperature of the air. The ID is also influenced by the fuel temperature. The second phase of combustion is called as period of rapid

combustion or premixed combustion. In this phase the air-fuel mixture undergoes rapid combustion, therefore the pressure rise is rapid and releases maximum heat flux. The third phase of combustion is called as period of controlled combustion. In this period, the fuel droplets injected during the second stage burns faster with reduced ID due to high temperature and pressure. In this third phase the pressure rise is controlled by the injection rate and the combustion is diffusive mode, as shown in Fig.12.

The lower calorific value (LCV) of PBD is less than PD fuel. Fig. 10 shows the variation of cylinder pressure with respect to crank angle at maximum output of 3.72 kW. It is observed that, the PBD is burning close to TDC and the peak pressure is slightly higher than that of PD fuel; even though the PBD is having lower value of LCV. The reason is attributed to the higher bulk modulus of the PBD. When, a high density (or high bulk modulus) fuel is injected, the pressure wave travels faster from pump end to nozzle end, through a high pressure in-line tube [21]. This causes early lift of needle in the nozzle, causing advanced injection. Hence, the combustion takes place very close to TDC and the peak pressure slightly high due to existence of smaller cylinder volume near TDC. Therefore the reason is attributed to the combined effect of advanced injection and lower value of heat rejection, which occurs due to prevalence of smaller cylinder volume (or surface area) near TDC.

6.2.1 Net heat release rates

Fig. 13 shows the net heat release rate (HRR). A noticeable change in combustion phases was observed between PBD and PBD_H. The peak value of premixed combustion was more for PBD, than that of PBD_H, and the diffusive combustion phase was more for PBD_H, than that of PBD. This is due to poor mixing of PBD with the surrounding air because of its high viscosity. At the time of ignition, less quantity of air-fuel mixture is prepared for combustion with PBD_H. This is due to faster evaporation of the preheated biodiesel. Therefore, more burning occurs in the diffusion phase rather than in the premixed phase. The increase in heat release is mainly due to better mixing and evaporation of PBD_H, which leads to improved burning.

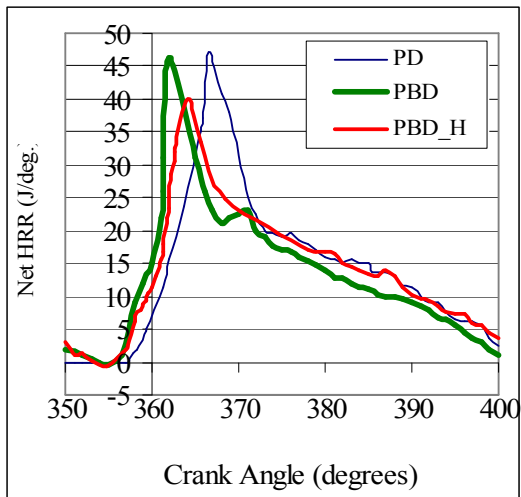


Fig. 13: Net heat release rates at maximum output

6.2.2 Exhaust gas temperatures

Fig. 14 shows the variation of exhaust gas temperature (EGT). The exhaust gas temperatures of PBD are lower than that of PD fuel, due to release of lower levels of thermal energy. However, the exhaust gas temperature of PBD_H is higher than that of PBD, which indicates the improved combustion due to high rate of evaporation and improved spray characteristics.

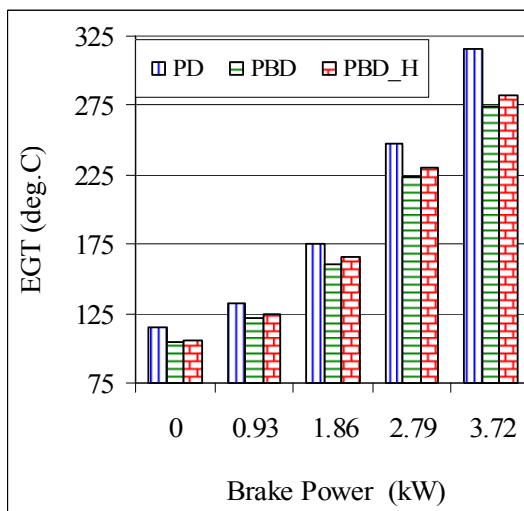


Fig. 14: Exhaust gas temperatures

6.3 Exhaust gaseous emissions

The exhaust gas emissions (NO, HC, CO, and Smoke) of the engine are measured with the following instruments, shown in the Table 4. The

table 5 shows the technical specifications of the exhaust gas analyzer.

Table 4: Instruments used to measure exhaust emission

Exhaust Emissions	Instrument	Model
NO, HC, CO	MRU Exhaust Gas Analyzer, Germany	Delta 1600 L
Smoke (soot)	A V L Smoke Meter, Graz-Austria	409 D

Table 5: Specifications of the Exhaust Gas Analyzer

Gaseous Emission	Range	Precision	Resolution
NO	0-2000 ppm	+/- 5 ppm	1 ppm
HC	0-20000 ppm (n-hexane)	+/- 12 ppm	1 ppm
CO	0-1500 % volume	+/- 0.06 %	0.01 %

6.3.1 Nitric oxide emission

In diesel engines, the combustion process mainly forms nitric oxide (NO) emission. Therefore, only NO is measured with the exhaust gas analyzer. The NO emissions are plotted in the bar chart shown in the Fig. 15 and the observations made are as follows:

Results show that for all the fuels the increased engine load promoting NO emission as shown in Fig. 15. Since the formation of NO is very sensitive to temperature, therefore higher loads promote cylinder charge temperature, which is responsible for thermal (or Zeldovich) NO formation. The presence of oxygen (11%) in PBD leads to improvement in oxidation of the nitrogen available during combustion. This will raise the combustion bulk temperature responsible for thermal NO formation.

The PBD having long carbon chain (C_{16} - C_{24}) is producing more NO than that of PD having both medium (C_8 - C_{14}) as well as long chain (C_{16} - C_{28}) as shown in Fig. 1 and 15. The increase in NO emission might be an inherent characteristic of PBD due to the presence of 51.8 % of mono-unsaturated fatty acids (MUFA) and 19% of poly-unsaturated fatty acids (PUFA) as shown in figure 2 and 3. That

means, the long chain fatty acids such as oleic ($C_{18:1}$) and linoleic ($C_{18:2}$) are responsible for higher levels of NO emission [22].

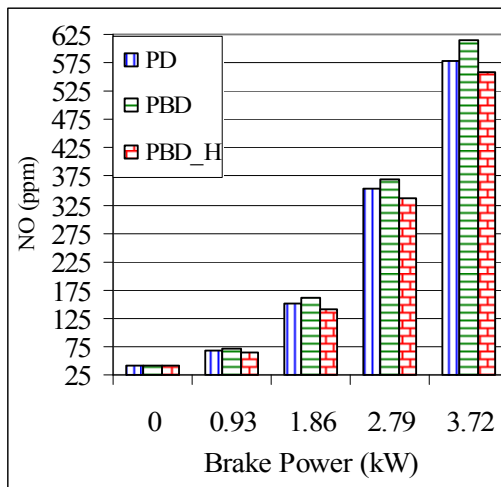


Fig. 15: Nitric oxide emission

The production of more NO with PBD fueling is also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the inline-fuel injection system. Higher bulk modulus leads to a more rapid transfer of the pressure wave from fuel-pump end to the fuel-injector needle, causes an earlier needle lift. The earlier needle lift causes an advanced (or early) injection (or combustion), which contributed towards large premixed combustion, and hence responsible for thermal (or Zeldovich) NO production.

The fuel spray properties may be altered due to differences in viscosity and surface tension. The spray properties affected may include droplet size, droplet momentum, degree of mixing, penetration, and evaporation. The change in any of these properties may lead to different relative duration of premixed and diffusive combustion regimes. Since the two burning processes (premixed and diffused) have different emission formation characteristics, the change in spray properties due to preheating of the PBD are lead to reduction in NO formation. The reason is attributed to reduced intensity of premixed combustion regime (Fig. 13) due to slightly retarded injection, better evaporation, and well mixing of PBD_H due to its low viscosity at preheated temperature of 50 °C.

6.3.2 Hydro carbon emission

Fig. 16 shows that for all fuels the unburned hydrocarbon (HC) emissions are indicating, a decreasing trend first and then increasing trend with the power output. The reason for higher level of HC at '0' kW power output is due to the flame quenching and cooled layer of the charge near the cylinder wall during the cold start.

The HC emissions of the PBD are less than that of PD fuel. The reason for lower HC emissions is due to inherent presence of oxygen (11%) in the molecular structure of the biodiesel. The PBD_H is producing lower levels of HC emissions as compared to that of PBD. The reason is attributed to better spray pattern (due to its lower viscosity) and evaporation (due to temperature of 50 °C), which leads to efficient combustion. Therefore, the lower HC levels of PBD_H are due to the combined effect of lower viscosity, presence of oxygen and higher CN as compared to that of PD fuel.

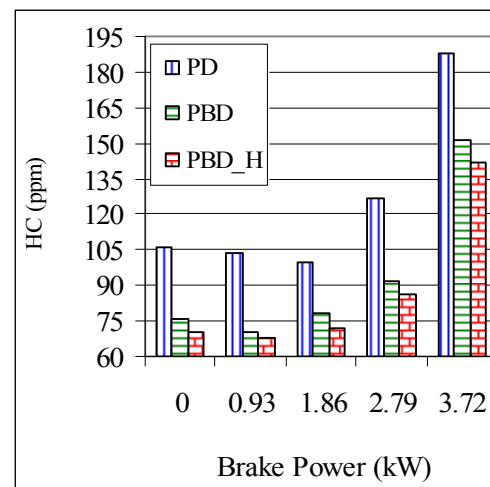


Fig. 16: Hydrocarbon emissions

6.3.3 Carbon monoxide

For both the fuels, the increasing trend of carbon monoxide (CO) emission levels are observed with power output as shown in Fig. 17. This increasing trend of CO emissions is due to increase in volumetric fuel consumption (due to its lower calorific value) with the engine output power. The CO emission level of PBD is less than that of PD fuel. The CO emission levels are further reduced for PBD_H, due to reduced viscosity, density and increase in evaporation rate.

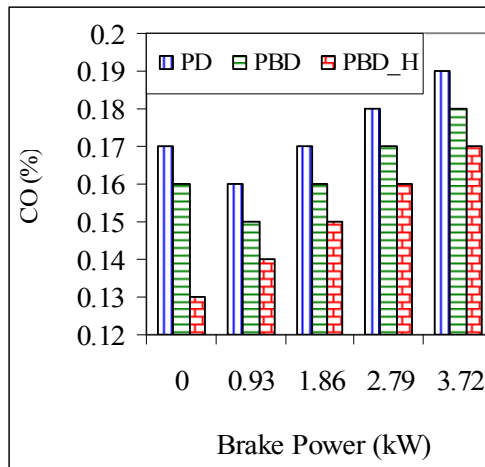


Fig. 17: Carbon monoxide emission

6.3.4 Smoke emission

The Fig. 18 shows that, the smoke emission increases with engine load for all the above fuels. This increasing trend is attributed to the increase in volumetric fuel consumption with the power output. At lower power outputs (0 kW and 0.93 kW), the PBD showed a slightly higher level of smoke than that of PD fuel. The reason is attributed to poor quality of air-fuel mixing. A portion of the fuel-rich mixture may fail to burn, was emitted as smoke.

The PD fuel at higher loads showed a higher level of smoke than PBD, the reason is due to presence of aromatics (Fig. 4). Especially, the presence of branched and ring (multi-ring or polycyclic) structures of the PD fuel can increase the exhaust smoke [23]. And this increase in smoke emission was due to the higher boiling point and high thermal stability of aromatic hydrocarbons [24]. The increase in smoke of PD fuel is also because of the lower levels of oxygen present in the PD fuel.

The biodiesel are emitting lower levels of smoke as compared to that of PD fuel under similar operating conditions. This is probably because of the inherent oxygen present in the biodiesel, which improves the combustion. The oxygen content in PD and PBD are 0.3%, and 11% respectively. Therefore, it is also concluded that, the increase of oxygen in the fuel tends to reduce the smoke (soot) emission for all power outputs as shown in the Fig. 18. However, the smoke emission is increasing for PBD_H, due to late phase of combustion, particularly increase in

diffusive combustion (heat release) as compared to that of PBD fuel.

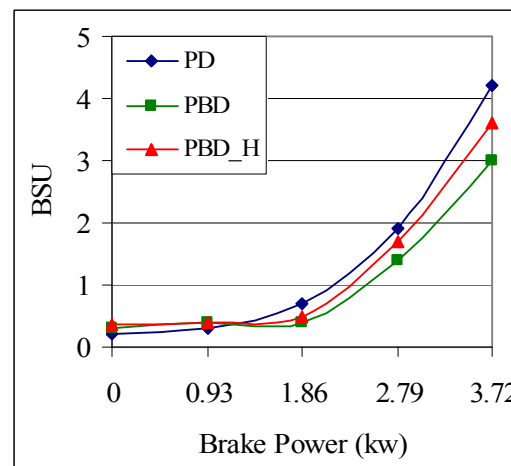


Fig. 18: Smoke emission

7 Conclusions

The present work confirms the influence of the higher bulk modulus of biodiesel on injection and combustion timing with the 'in-line' fuel injection systems. The advanced injection timing results in the increased NO emission with long chain pongamia biodiesel.

The increase of NO emission is due to the combined effect of higher bulk modulus, and presence of unsaturated fatty acids (MUFA and PUFA) and oxygen

The performance of the engine is increased, when the biodiesel is injected at diesel fuel viscosity.

Decrease in premixed combustion and increase in diffused combustion is observed with preheating. The reduction in peak value of premixed combustion leads to the reduction of NO emission.

The presence of oxygen in biodiesel improves the combustion and hence lowers the exhaust emissions.

Except smoke (soot), all the remaining emissions are reduced significantly with preheating of PBD. Improvement in diffused combustion is responsible for these increased smoke levels particularly at higher loads.

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