Australian Journal of Crop Science

AJCS

AJCS 7(9):1343-1349 (2013) ISSN:1835-2707

Experimental analysis of combustion characteristics of biodiesels obtained from two oil seed crops with different raw material compositions

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Abstract

The objective of the present study is to experimentally investigate the combustion characteristics of two biodiesels obtained from two oil seed crops, rice bran and palm. To determine their usefulness as alternative fuels, the combustion characteristics of the two biodiesels are compared with petro-diesel. In addition, the oxides of nitrogen (NO_X) and smoke emissions were measured and compared with petro-diesel. A single cylinder air-cooled direct injection (DI) diesel engine developing a power output of 4.4 kW at the rated speed of 1500 rpm was used for the experimental studies. The combustion and emission parameters were studied at 25%, 50%, 75%, and 100% of the rated load. Using a piezoelectric transducer with a range of 0 to 250bar, cylinder pressure history was measured. The heat release rates were determined from the cylinder pressure history. The actual start of injection (SOI) was calculated based on the negative heat release in the heat release diagram. Similarly, the cumulative heat release and combustion duration were also measured from the heat release diagram. The actual SOI was found to be earlier for rice bran biodiesel as compared to palm biodiesel, whereas the SOI was observed to be earlier for palm biodiesel as compared to diesel. The ignition delay for rice bran biodiesel was higher as compared to that of palm biodiesel. The ignition delay of diesel was found to be lower when compared to the biodiesels. It was observed that diesel produces higher peak pressure at all loads than the other fuels under investigation, while palm biodiesel exhibits higher peak pressures than rice bran biodiesel at all loads. At full load conditions, the peak pressure of diesel, palm biodiesel, and rice bran biodiesel was found to be 75.2, 69.1, and 65.3bar respectively. As compared to diesel, the increase in NO_X emissions were found to be 12% for rice bran biodiesel and 7% for palm biodiesel at full load. Rice bran biodiesel exhibits lower smoke density as compared to diesel and palm biodiesel. The reductions in smoke density were 9% and 18% with palm and rice bran biodiesels respectively as compared to diesel at full load.

Keywords: Combustion; emissions; fatty acid composition; palm biodiesel; rice bran biodiesel.
Abbreviation: aTDC_after top dead center; ; bTDC_before top dead center; CA_crank angle; cc_cubic centimeter; CO_carbon monoxide; DI_direct injection; HC_hydrocarbons: MUP_mechanical unit pump; NaOH_sodium hydroxide; NO_X_oxides of nitrogen; SOI_start of injection.

Introduction

Alternate fuels as diesel substitutes need to be developed to fulfill the energy demands in the future for developing countries. Therefore, researchers show interests in developing the alternative fuels from renewable sources. Vegetable oils, animal fats, and their derivatives, particularly methyl esters also known as biodiesels, are of considerable interest as alternative source of diesel fuels. Organic seed oils such as pongamia, soybean, cottonseed, rapeseed, jatropha, & palm oils, and their esters are considered as viable alternative types of fuel because they are renewable, non-toxic, and biodegradable and they produce lower emissions and closer combustion characteristics compared to diesel (Ramadhas et al., 2004; Anjana and Ram, 2000; Lance and Anderson, 2004; Hemanth, 2005; Martin et al., 2005; Hemmerlein et al., 1991). Biodiesel derived from rice bran and palm oils can be considered as significant diesel substitutes because of their high productivity and lesser cost (Sarin et al., 2007; Arumughan et al., 2004). There was not much research has been reported on biodiesel production from rice bran as compared to the other non-edible oils. The presence of active lipase in the bran and lack of economical stabilization methods made the usage of bran as livestock feed or boiler fuel and most rice bran oil produced is not of edible grade. Therefore, rice bran can be effectively utilized for biodiesel production (Yi-Hsu and Vali, 2005). As a residue from food production, rice bran does not require land which might be used for food production. The projected potential yield of crude rice bran oil is about eight million metric tons if all rice bran produced in the world were to be harnessed for oil extraction (Arumughan et al., 2004). Similarly, surplus palm crops are available in South Eastern countries like Thailand and Malaysia (Sarin et al., 2007). Many researchers have investigated the combustion, performance, and emission characteristics of vegetable oils and their esters in diesel engines. Kinoshita et al., (2003) have investigated the

Table 1. Fatty acid composition (in wt %) of rice bran and palm biodiesels.

Fatty acid chain and C:N	Rice bran biodiesel	Palm biodiesel
Lauric (C12:0)	0.1	0.2
Myristic (C14:0)	0.3	2.7
palmitic (C16:0)	12.7	49.2
Stearic (C18:0)	8.3	8.8
Oleic (C18:1)	28.9	31.3
Linoleic (C18:2)	36.6	7.5
Linolenic (C18:3)	13.1	0.3

In C: N, C indicates the number of carbon atoms and N the number of double bonds of carbon atoms in the fatty acid chain.

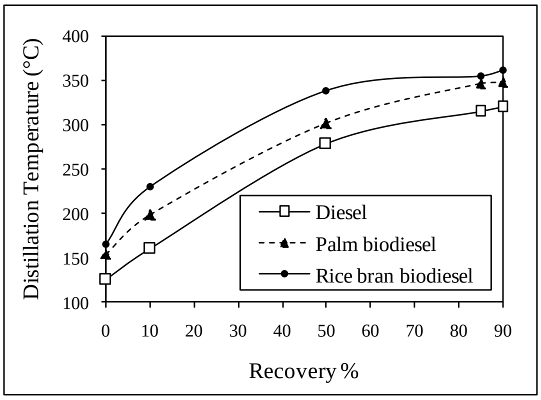

Fig 1. Distillation temperatures of diesel, palm biodiesel, and rice bran biodiesel to compare their volatility characteristics

combustion and emission characteristics of rapeseed and palm oil methyl esters and compared with gas oil in naturally aspirated water-cooled small direct injection (DI) diesel engine and swirl-chamber diesel engine. The authors found that the ignition delay of palm oil methyl ester was lower when compared to gas oil. Similarly rapeseed oil methyl ester showed a longer ignition delay as compared to gas oil. Soybean oil methyl ester and its blends were analysed (Zhang and Van Gerpen, 1996) in a four cylinder DI diesel engine. From the combustion study on blend of diesel and methyl tallowate, it was found that the peak rate of heat release for blend had found to be lower than the petro-diesel **(**Yu et al., 2002**)**. Sinha and Agarwal (2005) have investigated and stated that the peak pressure and rate of pressure rise were higher for B20 fuel (blend of 80% diesel and 20% rice bran biodiesel by volume) at low engine loads (up to 10% load) but becomes lower when the engine load is increased. Oxides of nitrogen (NO_X), carbon monoxide (CO), and smoke emissions were slightly lower for soybean biodiesel as compared to diesel, whereas a reduction of about 50% in hydrocarbon (HC) emission was found with soybean biodiesel compared to diesel (Scholl and Sorenson, 1993). The complete combustion due to fuel borne oxygen in biodiesel reduces CO, HC, and smoke emissions (Kalam et al., 2003; Kalligeros et al., 2003). A decrease of 32%, 59%, and 8.6% was found in NO_X, CO, and HC respectively with the olive oil methyl ester as compared to diesel (Dorado et al., 2003). When compared to diesel, HC and CO had decreased; while NO_X emission increased for methyl ester of rapeseed oil and its blends with diesel (Labeckas and Slavinskas, 2006). The objective of the present study is to experimentally investigate the combustion characteristics of two biodiesels obtained from two oil seed crops, rice bran and palm. Biodiesel derived from palm oil is more saturated while from rice bran oil is more unsaturated in nature. In addition, to determine their usefulness as alternative fuels, their combustion and emission characteristics are compared with petro-diesel.

Results

Fuel properties

The fatty acid profiles of rice bran and palm biodiesel are given in Table 1. The different fuel properties of diesel, rice bran biodiesel, and palm biodiesel as determined by the methods specified in ASTM standards are summarized in Table 2**.** The distillation temperatures for test fuel are shown in Figure 1. In the entire range of recovery, the distillation temperatures of palm biodiesel were found to be lower than that of rice bran biodiesel. Hence palm biodiesel may have better volatility compared to rice bran biodiesel. However, diesel exhibits a better volatility than the other two fuels.

Combustion characteristics

The actual start of injection (SOI), ignition delay, and start of combustion at full load conditions are illustrated in Figure 2. The actual SOI and start of combustion were calculated based on the dip in the heat release rate diagram based on the literature Zheng et al., (2008) procedure, which is discussed in the subsequent material and method section in a detailed manner. The variation of heat release rate with crank angle for all the fuels tested in the engine at full load is shown in Figure 3. At full load conditions, the maximum heat release occurs at uncontrolled combustion phase and it is higher for diesel (72.6 J/deg at 3° bTDC at full load) as compared to other fuels as seen in Figure 3. Similarly, the maximum heat release for palm and rice bran biodiesels are 67.8 J/deg exactly at TDC and 62.2 J/deg at 2° aTDC respectively. The variation of cumulative heat release with crank angle at full load is shown in Figure 4. The variation of cylinder pressure with crank angle at full load is shown in Figure 5, while Figure 6 compares the variation of peak pressure with load for the test fuels. It was observed that diesel produces higher peak pressure at all loads than the other fuels under investigation. Palm biodiesel exhibits higher peak pressures than rice bran biodiesel at all loads.

Table 2. Measured fuel properties of diesel, rice bran, and palm biodiesels.

Fuel property	Unit	Diesel	Rice bran biodiesel	Palm biodiesel
Kinematic viscosity at 40°C	cSt	2.62	4.7	4.1
Cetane number	-	48	51	54
Density at 15°C	kg/m^3	830	886	879
Net heating value	MJ/kg	42	36.3	37.1
Distillation temperature	°C			
50% recovery		278	339	302
90% recovery		320	361	348

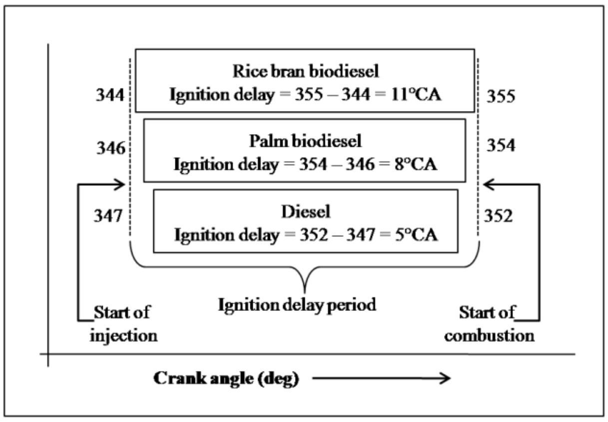

Fig 2. The actual SOI, ignition delay, and start of combustion of test fuels at full load conditions.

At full load conditions, the peak pressure of diesel, palm biodiesel, and rice bran biodiesel was found to be 75.2, 69.1, and 65.3bar respectively. Figure 7 shows the variation of combustion duration with load for the test fuels. The duration of combustion increases with increase in load for all the fuels due to increase in mass of fuel injected.

Emission characteristics

The variation of NO_X and smoke with load is depicted in Figures 8 and 9 respectively. As compared to diesel, the increase in NO_X emissions were found to be 12% for rice bran biodiesel and 7% for palm biodiesel at full load respectively. The smoke emission of rice bran biodiesel was the lowest as compared to the rest of the fuels at all loads. The reductions in smoke density are 9% and 18% with palm and rice bran biodiesels respectively as compared to diesel at full load.

Discussion

Combustion characteristics

From figure 2, it can be observed that the actual SOI is earlier for rice bran biodiesel as compared to palm biodiesel. Similarly, the actual SOI is earlier for palm biodiesel as compared to diesel. This can be explained as follows. The bulk modulus, which can be thought of as a resistance to compression, is dependent on the amount of free space available between molecules. For hydrocarbon fuels compressibility decreases as the density of the molecular structure increases (Szybist et al., 2005). Therefore, bulk modulus increases with increase in density. Also from Table 2, it can be seen that the density of rice bran biodiesel is higher than that of palm biodiesel. Similarly, the diesel has a lower density as compared to palm biodiesel. Hence it can be said that the rice bran biodiesel can have a higher bulk modulus than palm biodiesel. In a same fashion, the bulk modulus of palm biodiesel could be higher as compared to diesel. In addition, the presence of double bond in biodiesel fuels can increase the bulk modulus; thereby advancing the injection timing. Due to higher bulk modulus, the pressure waves generated by the pump plunger travels faster from pump end to the injector end; causes premature injection (Bakar and Firoz, 2005; Caresana, 2011; Kegl and Hribernik, 2006; Tat et al., 2007). Similarly it can be seen from Figure 2 that the ignition delay for rice bran biodiesel is higher as compared to that of palm biodiesel. This is believed due to the increased cetane number of palm biodiesel as compared to rice bran biodiesel (cetane number of palm biodiesel: 54, rice bran biodiesel: 51). Although diesel has a lower cetane number (48); its ignition delay found to be lower while comparing with the other test fuels. This is because of the improved atomization and better mixing in case of diesel due to its lesser viscosity. It can be observed that though the ignition delay of diesel is lower for diesel (Figure 2), it has a maximum heat release rate as compared to the other fuels (Figure 3). This can be correlated with the combined effect of heating value and viscosity. The net heating value of rice bran and palm biodiesels were found to be 36.3 and 37.1 MJ/kg respectively, which are 13.6% and 11.7% lesser than that of diesel that is 42 MJ/kg. Fuel with higher heating value can produce more amount of heat energy in a given time period and for a given fuel volume. In addition, if the viscosity is lesser, the evaporation rate will be faster and a larger amount of mixture can be expected for combustion. Similarly the maximum heat release rate of palm biodiesel was found to be higher (though it has a smaller ignition delay period) as compared to rice bran biodiesel. Diesel has higher cumulative heat release and rice bran biodiesel has a lesser cumulative heat release while the value of palm biodiesel lies in between these two fuels (Figure 4). The variation of cylinder pressure with crank angle at full load (Figure 5) indicates that the peak pressure of diesel occurs closer to TDC which is 72.2bar at 9°CA aTDC. This is believed due to the fact that the diesel can have a better atomization and mixing due to its lower viscosity when compared to other test fuels. For palm and rice bran biodiesels, the peak pressure and its occurrence are 68.1bar at 12°CA aTDC and 65.3bar at 14°CA aTDC respectively. The order of occurrence of peak pressure was found to be the same as that of

Table 3. ASTM standards for fuel properties determination.

Property	Unit	ASTM Standard
Density	kg/m^3	D 1298
Kinematic viscosity	cSt	D 445
Net heating value	MJ/kg	D 240
Cetane number	-	D 613
Distillation temperatures	°C	D 86

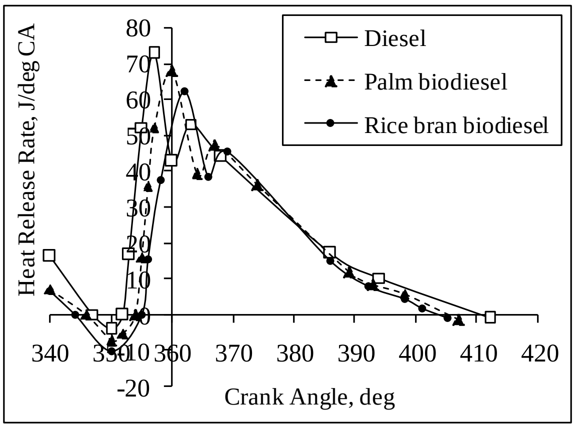

Fig 3. Variation of heat release rate with crank angle at full load conditions shows the magnitude and occurrence of peak heat release rate for diesel, palm biodiesel, and rice bran biodiesel.

Table 4. Specification of test engine used to investigate the combustion and emission characteristics of different test fuels at various loads.

Parameters	Specification
Make	Kirloskar
Model	TAF-1
No. of cylinders	One
Type of cooling	Air cooled
Bore x Stroke	87.5 x 110 mm
Compression ratio	17.5:1
Piston bowl	Hemispherical
Rated power	4.4 kW @ 1500 rpm
Injection opening pressure	200 bar
Fuel injection timing	23° CA bTDC

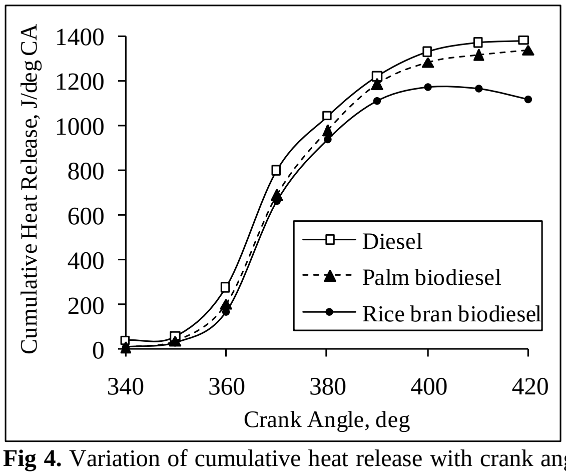

Fig 4. Variation of cumulative heat release with crank angle at full load conditions shows the cumulative heat release for same crank angle duration for diesel, palm biodiesel, and rice bran biodiesel.

maximum heat release rate. The variation of peak pressure with load (Figure 6) shows that diesel produces higher peak pressure at all loads than the other fuels under investigation. Palm biodiesel exhibits higher pressures than rice bran biodiesel at all loads. At full load and 75% of load, the combustion duration (Figure 7) appears to be lower for rice bran biodiesel than for palm biodiesel and diesel. However the changes appear to be erratic at 25% and 50% load conditions and do not direct to any meaningful conclusions on the relationship between combustion duration and fuel properties.

Emission characteristics

The NO_X of rice bran biodiesel is higher than that of diesel and palm biodiesel (Figure 8). The increase of NO_X in rice bran biodiesel is believed due to contribution of higher amount of polyunsaturated fatty acids that present in rice bran biodiesel as compared to palm biodiesel. Increasing density may also result in higher NO_X as the fuel injectors inject a constant volume, but larger mass of more dense fuels is injected. From the fuel properties it can be observed that diesel has a lower density as compared to palm biodiesel; similarly, the density of palm biodiesel is lower than that of rice bran biodiesel. The increase in NO_X emissions were found to be 7% for palm biodiesel and 12% for rice bran biodiesel at full load operation when compared to diesel. Smoke is resulted as a product of the incomplete combustion process, particularly at high loads. It is observed that that the smoke increases with increase in load for all the test fuels (Figure 9). A minor difference in smoke was found between test fuels at part loads, whereas a considerable difference was observed at elevated loads. The reductions in smoke density are 19% and 9% with rice bran and palm biodiesels respectively as compared to diesel at full load. This reduction in smoke with biodiesel is believed due to the presence of supplementary oxygen availability. Due to the added oxygen, smoke may be reduced at the rich mixture of fuel spray and the cooler part of spray impingement of combustion chamber wall. Smoke can also be related to air-fuel ratio, i.e. fuels with higher air-fuel ratio need more amount of air for complete combustion as compared to fuels which have lower air-fuel ratio in a given time. The stoichiometric air-fuel ratio for biodiesel derived from palm, coconut, and rapeseed oils were found to be lower than that of diesel (Kinoshita et al., 2003; Kinoshita et al., 2006).

Materials and methods

Transesterification of rice bran and palm oils

The source vegetable oils (rice bran oil and palm oil) were obtained from Annai Biocrops Pvt. Ltd, Chennai. The biodiesels (methyl esters of rice bran and palm oils) were produced through transesterification. Transesterification is a process in which the reaction between triglyceride and alcohol occurs to produce alkyl ester and glycerol. The biodiesels were produced from 1000g of vegetable oil, 200g of methanol, and 5g of sodium hydroxide (NaOH) as a catalyst (generally the alcohol and the catalyst quantity are 20% and 0.3 to 0.5% of the parent vegetable oil respectively). The ester conversion ratio of rice bran and palm biodiesels were over 95%.

Fuel properties

The fuel properties were determined following the methods specified in ASTM standards as given in Table 3.

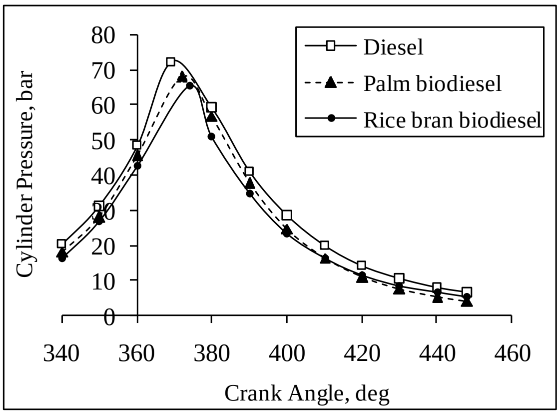

Fig 5. Variation of cylinder pressure with crank angle at full load conditions shows the magnitude and occurrence of peak pressure for diesel, palm biodiesel, and rice bran biodiesel.

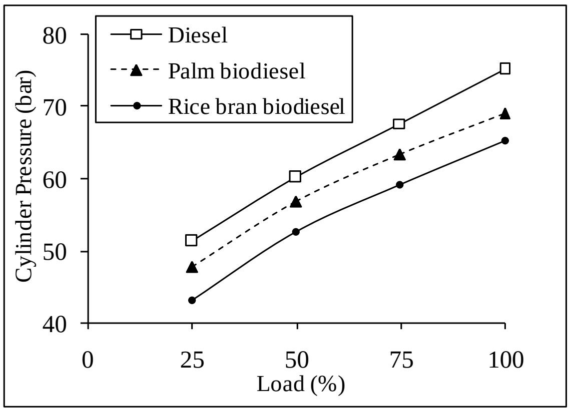

Fig 6. Variation of peak pressure with load shows the magnitude of peak pressure at various engine loads for diesel, palm biodiesel, and rice bran biodiesel.

The properties such as density, kinematic viscosity, cetane number, heating value, and distillation characteristics were measured at ITALAB Pvt. Ltd, Industrial Testing and Analytical Laboratories (an ISO 9001: 2000 certified organization), Chennai, India. The fatty acid profile analysis was done at the Tamil Nadu Oil Seeds Association, Chennai, India. The fatty acid composition of biodiesel products were determined using Gas Chromatography (GC) analysis.

Engine experimental set-up and test procedure

A single cylinder air-cooled DI diesel engine developing a power output of 4.4 kW at the rated speed of 1500 rpm was used for the experimental studies. The technical specifications of the engine are given in Table 4. The engine was coupled to a swinging field electric dynamometer exciting type DC generator and loaded by electrical resistance to apply different engine loads. The combustion and emissions were studied at 25%, 50%, 75%, and 100% (full load) of the load corresponding to the load at maximum power at an average speed of 1500 rpm. A mechanical unit pump (MUP) of helical plunger type made by Mico Bosch was used to deliver the fuel to the multi-hole orifice with sac volume. An orifice meter connected to an air surge tank was attached to inlet manifold of the engine to measure airflow.

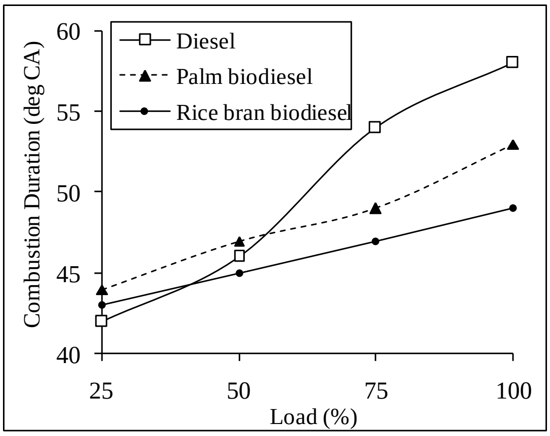

Fig 7. Variation of combustion duration with load for diesel, palm biodiesel, and rice bran biodiesel.

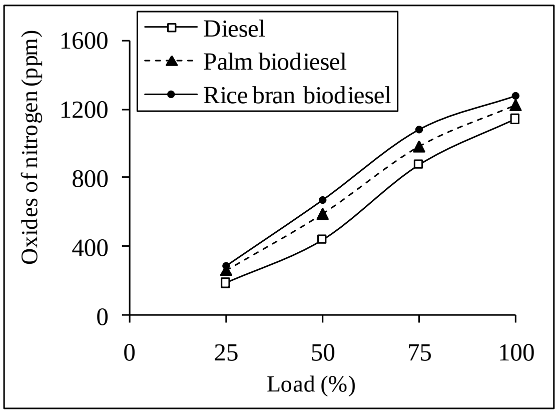

Fig 8. Variation of oxides of nitrogen with load shows the magnitude of NO_X emissions at various engine loads for diesel, palm biodiesel, and rice bran biodiesel.

The fuel flow rate was measured on volume basis (time taken for 10cc of fuel consumption was measured) using a burette and a stop watch. After the engine reached the stabilized working condition; the combustion and emission parameters were measured. Kistler piezoelectric transducer with a range of 0 to 250bar was used to measure the cylinder pressure history. The actual SOI also termed as dynamic injection timing is the crank angle point at which the fuel jet actually enters into the engine combustion chamber. The actual SOI and ignition delay were not experimentally determined in this investigation. They were calculated based on the dip in the heat release rate diagram and this method was used earlier by Zheng et al., (2008). The actual SOI was calculated based on the negative heat release in the heat release diagram. Since the fuel droplet absorbs heat from the cylinder, there is a negative heat release on the diagram. The point at which the first negative heat release starts is the dynamic injection time and the start of ignition delay period. Similarly, the point at where the first positive heat release is seen on the diagram is the end of ignition delay period (Zheng et al., 2008). The heat release rates were determined from the cylinder pressure history. The NO_X emission was measured with DELTA 1600-L make MRU OPTRANS 1600 exhaust gas analyzer. The smoke density was measured by Bosch make TI diesel tune, 114-smoke density tester. As per the specifications of the exhaust gas analyzer, the

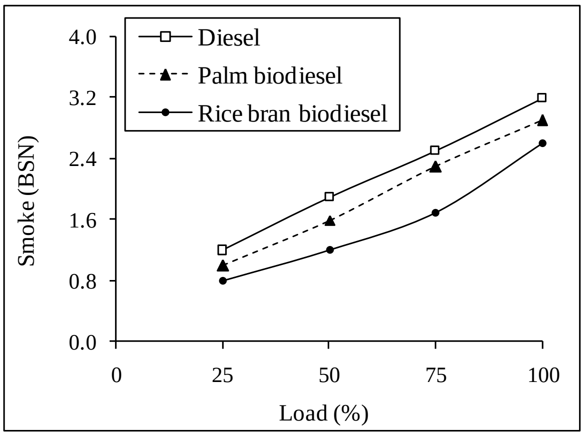

Fig 9. Variation of smoke with load shows the magnitude of smoke density at various engine loads for diesel, palm biodiesel, and rice bran biodiesel

maximum possible error in the measurement of NO_X and smoke density is ± 5%. Similarly, from the piezoelectric transducer specifications, the maximum possible error in the pressure measurement is ± 1%.

Conclusions

Experiments were carried out to investigate the combustion and emission characteristics of two potential biodiesels (palm and rice bran) with different raw material composition. The results were compared with petro-diesel in order to determine usefulness of these two biodiesels as alternative fuels. The actual start of injection was found to be earlier for rice bran biodiesel as compared to palm biodiesel at full load. Similarly, palm biodiesel showed earlier injection timing as compared to diesel at full load. The ignition delay of palm biodiesel was shorter than that of rice bran biodiesel but longer than that of diesel at full load. The peak heat release rate and peak pressure of palm biodiesel were higher than that of rice bran biodiesel but lower than that of diesel at full load conditions. As compared to diesel, the increase in NO_X emissions were found to be 12% for rice bran biodiesel and 7% for at full load. The smoke emission of rice bran biodiesel was the lowest as compared to the rest of the fuels. The reductions in smoke density are 9% and 18% with palm and rice bran biodiesels respectively as compared to diesel at full load. From the present study, it is concluded that the biodiesels derived from palm and rice bran oils with their different raw material composition are potential alternative fuel sources for diesel, which show relatively closer combustion characteristics and exhaust emissions to diesel. Future studies can be done by blending rice bran biodiesel with palm biodiesel in different ratios in order to realize better performance from these biodiesels. The present investigation is based on a short term engine test. However, the long term issues such as engine deposits, injector coking, and contamination of the engine due to the usage of biodiesel fuels may be necessary.

Acknowledgement

The authors thank Head of the Department-Mechanical Engineering, Anna University, Chennai, India, for providing adequate amenities to conduct the experiments in the laboratory and for his constant support.

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