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Emission and Combustion Characteristics of Jatropha Biodiesel Fuelled Single Cylinder Agriculture Engine

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Abstract

With increasingly stricter legislations worldwide and shrinking reserves of fossil fuels, biodiesel has emerged out as one of the most promising alternative fuel for diesel engines. However, one major drawback of biodiesel is that it produces higher NOx emissions than mineral diesel although the soot emissions are comparatively lower due to its different combustion characteristics. In the present work, Jatropha biodiesel has been proposed as an alternative fuel for powering existing diesel engine. Transesterification has been carried out for effective utilization of Jatropha oil. Thermal efficiency, brake specific fuel consumption(BSFC),smoke opacity, exhaust gas temperature(EGT),brake mean effective pressure(BMEP) have been measured for Jatropha oil. A comparable study is carried out on the basis of different performance curves, which are plotted for each proportion between thermal efficiency versus brake mean effective pressure(BMEP), smoke opacity versus brake mean effective pressure(BMEP) and brake specific fuel consumption (BSFC) versus brake mean effective pressure(BMEP). Transesterification process is a very effective process for reducing high viscosity of vegetable oils and bringing about changes at molecular level. Vegetable oils do not exhibit combustion related problems and the transesterification process produces a Bio-origin fuel that behaves almost like mineral diesel oil.

Keywords- Jatropha Biodiesel, Transesterification, NOx emission, Engine load

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I. INTRODUCTION

Increasing industrialization and motorization of the world has led to a steep rise for the demand of petroleum products. Petroleum based fuels are obtained from limited underground based reserves. These finite reserves are highly concentrated in certain regions of the world [1]. Hence, it is necessary to look for alternative fuels. The growing concern due to environmental pollution caused by the conventional fossil fuels and the realization that they are non-renewable has led to search for more environment friendly and renewable fuels [2, 3]. It is estimated that worldwide energy-related carbon dioxide emissions rise 43% between 2008 and 2035, reaching 43.2 billion metric tons in 2035 [1, 4].

Alternative fuels should be easily available, environment friendly and techno- economically competitive. The fuels of bio-origin may be alcohol, vegetable oils, biomass and biogas. Some of these fuels can be used directly while others need to be formulated to bring the relevant properties close to conventional fuels. For Diesel engines, a great deal of research effort has been oriented towards using vegetable oils and their derivatives as alternative fuels. Vegetable oils have comparable energy density, cetane number, heat of vaporization, and stoichiometric air/fuel ratio with mineral diesel[5]. In addition, the use of vegetable oil as fuel is less polluting than petroleum fuels. Some of these alternative fuels are Natural Gas (CH_4 Methane) now it is commercially used in the form of liquefied natural gas (LNG) or as compressed natural gas (CNG).

Vegetable oil based fuels are biodegradable, non-toxic, and significantly reduce pollution. The use of vegetable oils such as palm, soya bean, sunflower, peanut and olive oil as alternative fuels for diesel engines. Vegetable oils comprise 90 to 98% triglycerides and small amounts of mono and diglycerides. Triglycerides are esters of three fatty acids and one glycerol. These contain substantial amount of oxygen in its structure[6-7]. Fatty acids vary in their carbon chain length and in the number of double bonds [8]. Vegetable oils and their derivatives in diesel engines lead to substantial reduction in sulphur, carbon monoxide (CO), poly aromatic hydrocarbons (PAH), smoke, noise and particulate emissions[7]. Also, the contribution of bio fuels to greenhouse effect is insignificant, since carbon dioxide (CO_2) emitted during combustion is recycled in the photosynthesis process in the plants. However, the Kinematic Viscosity of vegetable oils is several times higher than that of diesel. The fuel modification is mainly aimed at reducing the viscosity to get rid of flow/atomization related problems.

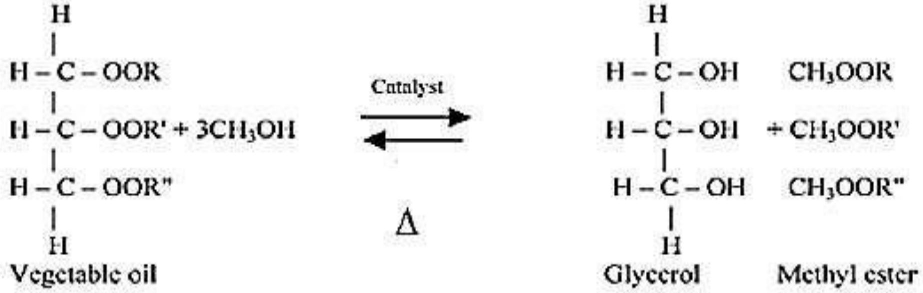
A. Biodiesel

Worldwide biodiesel production is mainly from edible oils such as soya bean, sunflower and canola oils. India, not being self-sufficient in edible oil production, hence, non-edible oil seeds available in the country is being tapped for biodiesel production. With the abundance of forest and plant based non-edible oils being available in India such as Karanja, Jatropha, Mahua, Sal, Neem and Rubber, attempt has been made to use esters of these non-edible oils as partial substitute for diesel shown in Table 1.

Table 1: Biodiesel fuel properties [9]

Biodiesel Feedstock Oil	*Kinematic Viscosity (mm^2/s)*	*Density (kg/m^3)*	*Heating Value (MJ/kg)*	*Cloud Point (^0C)*	*Pour Point (^0C)*	*Flash Point (^0C)*	*Cetane Number*	*Carbon Residue (% wt)*
Jatropha	*5.65*	*824*	*38.5*	*13*	*-*	*175*	*50*	*-*
Karanja	*6.87*	*897*	*37.9*	*-*	*-1*	*187*	*49*	*0.05*
Rapeseed	*7.2*	*883*	*37.37*	*-*	*-12*	*-*	*51*	*-*
Neem	*15*	*882*	*38.5*	*-*	*-*	*180*	*47*	*-*
Sunflower	*10*	*878*	*40.58*	*-*	*-*	*85*	*45-52*	*-*
Soyabean	*11*	*872*	*39.57*	*-*	*-*	*69*	*37*	*-*
Coconut	*3.36*	*966*	*36.1*	*-*	*-4*	*122*	*56*	*0.03*

Biodiesel has been reported as a possible substitute or extender for conventional diesel and is comprised of fatty acid methyl/ethyl esters, obtained from triglycerides by transesterification with methanol/ethanol, respectively. Chemically, biodiesel is defined as mono-alkyl alkaline esters of long chain fatty acids. It is produced by a chemical reaction of vegetable oils or animal fats with primary alcohols in presence of catalyst, usually a strong acid or base. They can be easily used in diesel engines and boilers as alternative fuels with minor modifications in the hardware. In transesterification of vegetable oils, a triglyceride reacts with an alcohol in presence of a strong acid or base, producing a mixture of fatty acid alkyl esters and glycerol. The stoichiometric reaction required 1 mole of triglyceride and 3 mole of alcohol. However, an excess of the alcohol is used to increase the yields of alkyl esters and to allow its phase separation from the glycerol formed.



Properties of bio-diesels are dependent on resources such as soybean, rapeseed, or animal fats etc., [10]. Biodiesel has higher cetane number compared to mineral diesel. Biodiesel contains 10–12% oxygen by weight, no aromatics and almost no sulphur.

Higher cetane number of biodiesel reduces the ignition delay and NOx emission during the initial combustion process. Exhaust emissions such as HC, CO, PM and smoke are also lower than that of mineral diesel [16]. Biodiesel has received a lot of attention because it can be used in diesel engines without major engine modifications [17-18].The following table shows a comparative study of mineral diesel and biodiesel.

Table 2: Standards for biodiesel compared to mineral diesel [11-15]

Fuel properties	*Mineral diesel*	*Biodiesel*	
	ASTM D975	*ASTM D6751*	*DIN 14214*
Density 15^0C (kg/m^3)	*850*	*880*	*860–900*
Viscosity at 40^0C (cSt)	*2.6*	*1.9–6.0*	*3.5–5.0*
Cetane number	*40 –55*	*Min. 47*	*Min. 51*
Calorific value (MJ/kg)	*42 – 46*	*–*	*35*
Acid value (mg KOH/g)	*0.062*	*Max. 0.50*	*Max. 0.5*
Pour point (^0C)	*–35*	*–15 to –16*	*–*
Flash point (^0C)	*60 – 80*	*Min. 100–170*	*>120*
Cloud point (^0C)	*–20*	*–3 to –12*	*–*
Cold filter plugging point (^0C)	*–25*	*19*	*Max. +5*
Carbon (wt %)	*84 – 87*	*77*	*–*
Hydrogen (wt %)	*12–16*	*12*	*–*
Oxygen (wt %)	*0–0.31*	*11*	*–*
Ash content % (w/w)	*0.01*	*0.02*	*0.02*
Oxidation stability (h, 110^0C)	*–*	*3 min*	*6 min*
Lubricity (HFRR, µm)	*685*	*314*	*–*

II. EXPERIMENTAL SETUP

The engine used for present investigation is a single cylinder, four stroke, water cooled, direct injection diesel engine. The engine is running at a rated speed of 1500 rpm. The test engine was connected with a single phase 220 V AC alternator, which was used to apply load to the engine. The Table 3 shows the technical specifications of the test engine.

Table 3: Test engine specification

Engine Parameters	*Specifications*
Manufacturer	*Kirloskar Oil Engine Ltd. India*
Engine type	*4-stroke, single cylinder,*
Rated power	*7.4 kW at 1500 RPM*
Bore/ stroke	*102 mm / 116 mm*
Displacement volume	*0.948 litre*
Compression ratio	*17.5:1*
Start of fuel injection timing	26^0 *BTDC*
Injection pressure	*200 bar*
Cooling type	*Water cooled*

A variac was used to precisely control the engine load. For in-cylinder pressure measurement, the test engine was equipped with a piezoelectric pressure transducer (Kistler; 6014C), charge amplifier (Kistler; 5015), rotary shaft encoder (Encoders India; ENC58/6) and a high-speed data acquisition system (Hi- Techniques). For measurement of exhaust gas temperature, a K-type thermocouple was installed in the exhaust manifold shown in Figure 1. Smoke opacity was measured using a smoke opacimeter (AVL; 437). Raw exhaust emission analyzer (AVL; 4000) was used for measurement of CO, HC, CO_2 and NO_X present in the exhaust gas.The air flow and fuel flow rates were measured using a U-tube manometer with the orifice and measuring burette respectively.

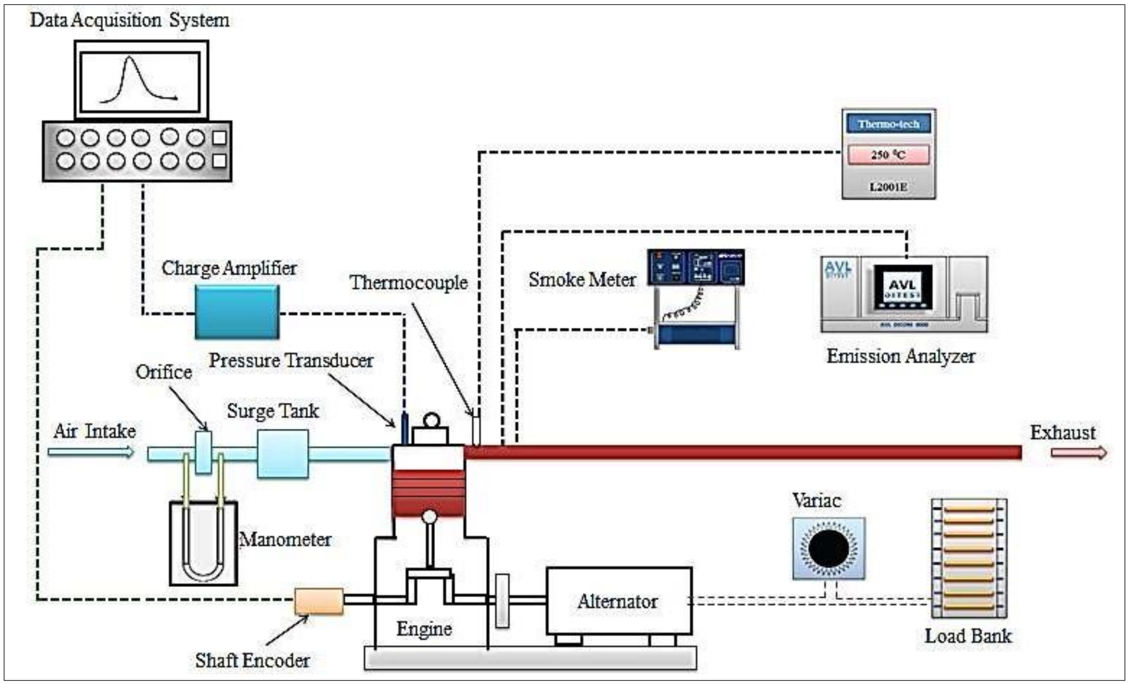


Fig. 1: Schematic of experimental setup.

The air flow rate was measured using equation 1 and 2.

$$(G_{air})_{theoretical} = A\,(2gH_w\rho_w\rho_a)^{0.5} \qquad (1)$$

where,

$(G_{air})_{theoretical}$ = Theoretical mass flow rate of air (kg/h)
A = Area of orifice (m^2) = $\pi/4 \times d^2$
d = Diameter of orifice = 17.7 mm
H_w = Height of water column in U-Tube manometer (m of H_2O)
ρ_w = Density of water at NTP = 995.24 kg/m^3 at 30^0C
ρa = Density of air at NTP = 1.293 kg/m^3
Actual mass flow rate of air

$$(G_{air})_{actual} = C_d \times A\,(2gH_w\rho_w\rho_a)^{0.5} \qquad (2)$$

where,

C_d = Coefficient of discharge of orifice = 0.62
The flow rate of fuel was measured using equation 3.

where
G_{fuel} = Flow rate of fuel, kg/h
t = Time, sec.
x = volume of fuel flow in time t, mL
ρ = Density of fuel, kg/m^3
The output load was calculated using equation 4.

$$\text{Output load (kW)} = V \times I \qquad (4)$$

where
V = Voltage generated by the alternator (volts)
I = Current generated by the alternator, when load was applied (amps)

III. RESULT AND DISCUSSION

The important chemical, physical and thermal properties of Jatropha biodiesel and mineral diesel are given in Table 4.

Table 4: Properties of test fuels

Test Fuels	*Test Fuel Properties*				
	Viscosity (mm^2/s)	*Density (g/cm^3)*	*Calorific Value (MJ/kg)*	*Flash Point (^{0}C)*	*Oxidation Stability (hr.)*
D100	*2.45*	*0.832*	*44.7*	*44*	*8.79*
JB100	*4.66*	*0.857*	*41.5*	*150*	*1.5*

To analyze the influence of fuel properties on single cylinder agricultural diesel engine characteristics, the most important combustion and emission characteristics, obtained with Jatropha biodiesel (JB100) and mineral diesel (D100), are compared and discussed in this section.

A. Engine Emission Characteristics

Variation of CO emissions for Jatropha biodiesel (JB100) and mineral diesel at different engine load is shown in Figure 2. Formation of CO emissions is due to the insufficient oxygen and time in the combustion chamber during the combustion process. The diesel engines are operating under lean mixture and emit lower CO. It is observed that JB100 show lesser CO emissions than mineral diesel at all engine loads. Due to intrinsic oxygen content in the esters, the oxygen availability for oxidation of CO is more in esters compared to mineral diesel which results in reduced CO emissions.

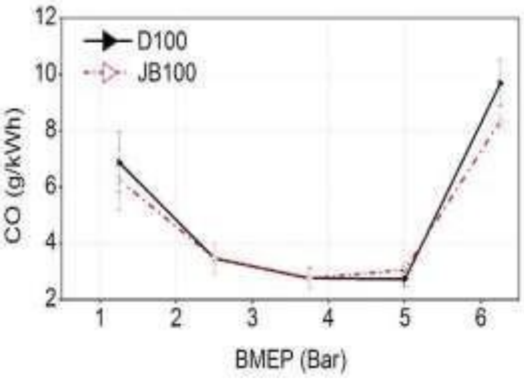


Fig. 2: Variation in CO with engine load

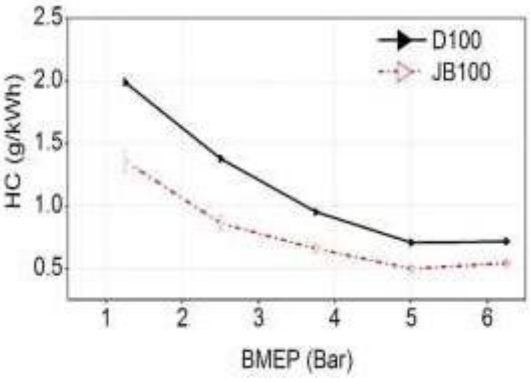


Fig. 3: Variation in HC with engine load

The variation of HC emissions with engine load for JB100 is shown in Figure 3. It can be seen that mass emissions of HC decreases as load increases for both the test fuels. But, raw emission of HC increases as the engine load increases. This may be due to the presence of fuel rich mixture at higher loads. There is slight reduction in HC emissions for JB100 at all engine loads compared to mineral diesel. The HC emission reduced with biodiesel due to the higher oxygen content and lower carbon and hydrogen content in the biodiesel compared with mineral diesel, these factors may trigger an improved and more complete combustion process, which help reduce HC emissions [18]

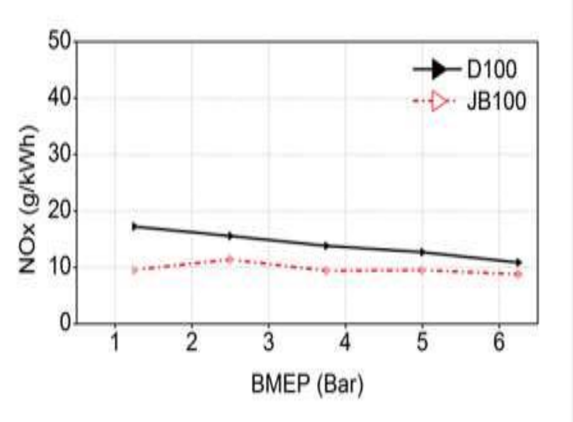


Fig. 4: Variation in CO with engine load

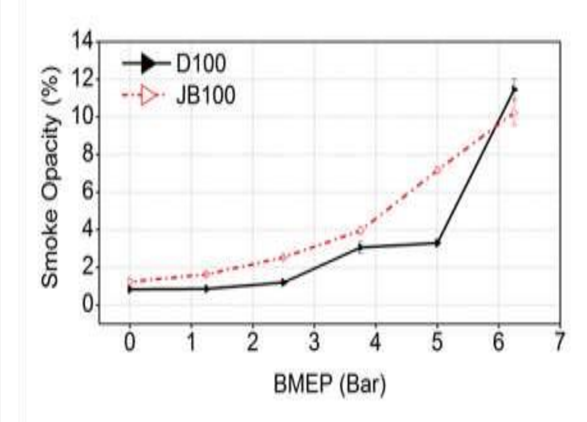


Fig. 5: Variation in HC with engine load

The NOx formation from atmospheric nitrogen is highly dependent on the temperature, which is due to high activation energy needed for the reactions involved, and these reactions are determined by the equivalence ratio, oxygen concentration and combustion temperature as well [18]. The oxygen content of biodiesel is an important factor in NOx formation because it causes increased local temperatures due to excess hydrocarbon oxidation, the maximum temperature during combustion increases, and the NOx formation also increases. The NOx level was found to be directly related to the combustion temperature while it was inversely related to the smoke and CO values [19-20]. The Jatropha biodiesel (JB100) showed slightly lower NO_x emission compared to mineral diesel at all engine loading condition shown in Figure 4. With increase in engine load, higher amount of fuel is injected in the combustion chamber, which leads to lower A/F ratio, leading to higher NOx formation but at the same time, higher amount of useful power is also produced, therefore although the volumetric emission of NOx increases but mass emission of NOx decreases [20].

Most of the smoke results from incomplete combustion of fuel hydrocarbons and some is contributed by the lubricating oil. They are highly undesirable as they reduce the visibility. The variation of Smoke (%) at various engine loads is shown in Figure 5 for JB100 and D100. From the figure, it is clear that smoke emissions slightly higher for JB100 compared to D100 may be due to the incomplete combustion. At full engine load JB100 produces slightly lesser smoke than mineral diesel. This could be due to the presence of oxygen molecule in the biodiesel chain, which enhances its complete burning as compared to diesel.

B. Engine Combustion Characteristics

The variation of cylinder pressure with crank angle for JB100 and D100 is shown in Figure 6. It can be seen that the both test fuels shows the same trend except for slight changes in values of pressure at various crank angle. One of the most important parameters in the combustion phenomenon is the ignition delay. The ignition delay is influenced by the cetane number of the fuel, compression ratio, engine speed, in-cylinder gas pressure, intake-air temperature, and fuel atomization characteristics [21]. The ignition delay is defined as the time interval between the start of injection (SOI) timing and start of combustion (SOC) timing. The ignition delay slightly decreases with use of biodiesel due to higher cetane number compared to mineral diesel [21]. At all engine loads, combustion starts earlier for JB100 than D100. Ignition delay for all fuels decrease as the engine load increases because the in-cylinder gas temperature is higher at higher engine loads, therefore it reduces the physical ignition delay period [22]. The maximum cylinder gas pressure of the JB100 is slightly higher than that of mineral diesel at higher engine load which may be due to the higher bsfc, cetane number, boiling point, oxygen content and advance in start of injection (SOI) timing.

Figure 7 shows the heat release rate for biodiesel (JB100) vis-à-vis mineral diesel (D100) at different engine operating conditions. In the beginning a negative heat release is observed because of the vaporization of the fuel accumulated during ignition delay and after combustion is initiated, heat release becomes positive. As the load increases, maximum heat release rate increases due to increase in fuel quantity injected. Biodiesel ignites earlier than mineral diesel due to shorter ignition delay. At higher engine load combustion starts earlier for JB100 compared to mineral diesel. Jatropha biodiesel (JB100) observed comparable HRR_{max} at no load condition while it observed lower at full load condition. This may be attributed to the higher kinematic viscosity compared to mineral diesel. Slightly shorter ignition delay was observed for JB100 which results into shorter mixture preparation time. This result into reduction in amount of energy released in premixed combustion phase and lower HRR_{max} [23].

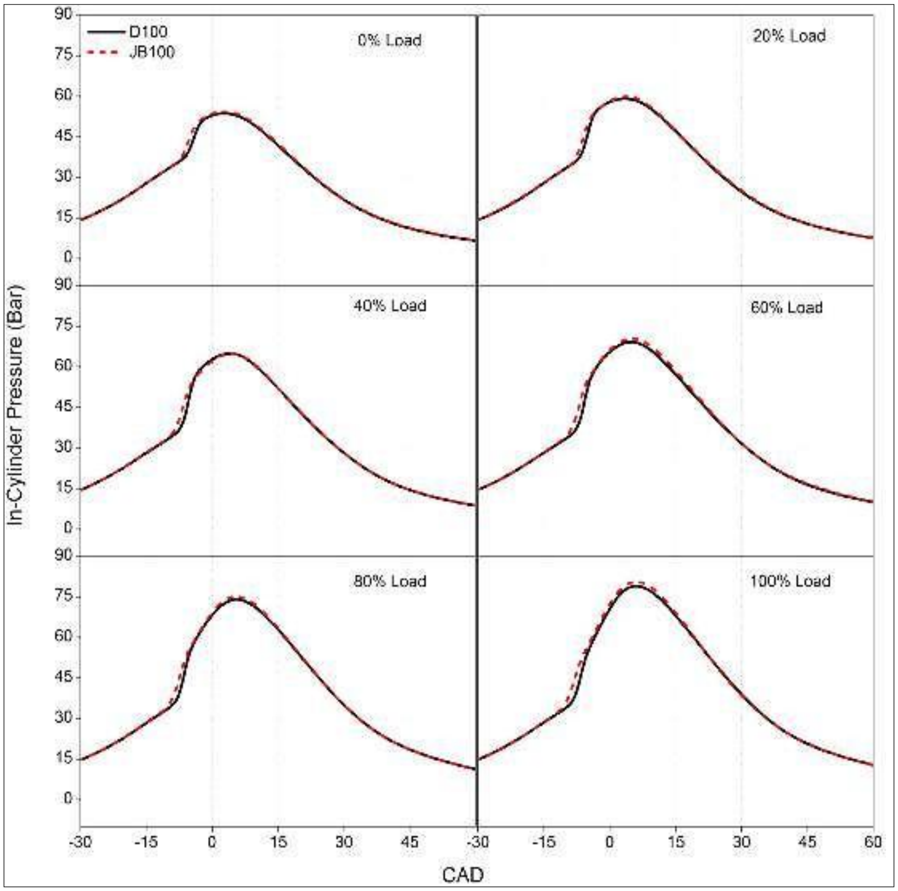


Fig. 6: Variation in in-cylinder pressure with crank angle

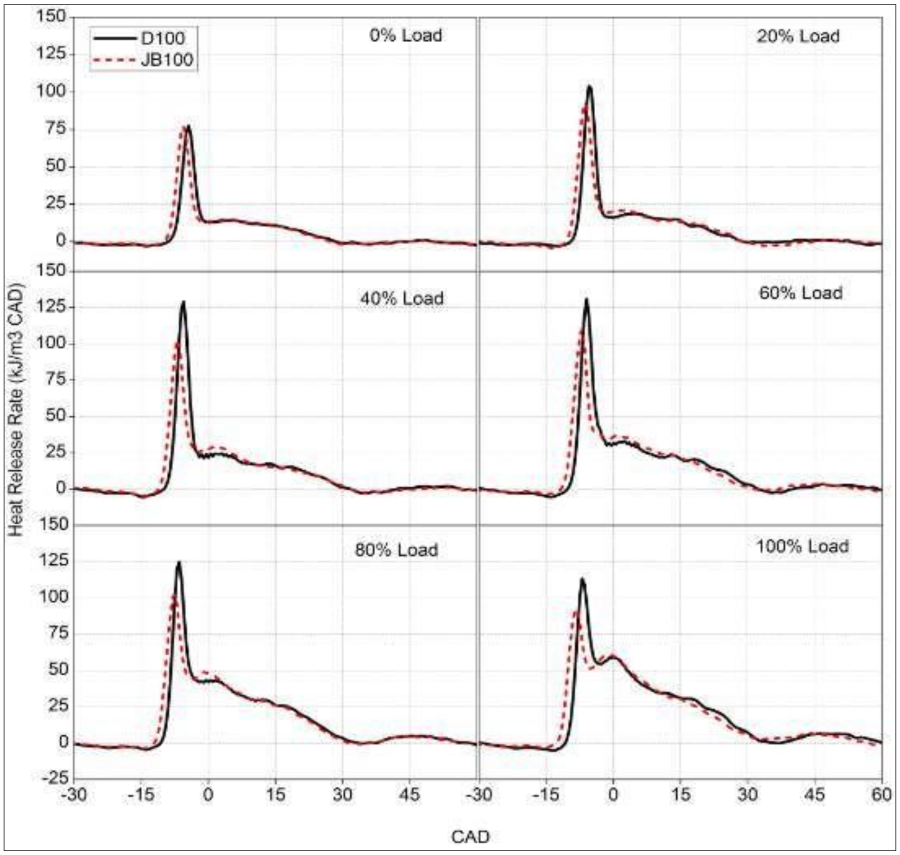


Fig. 7: Variation in heat release rate with crank angle

Figure 8 shows the crank angle for 10% mass burn fraction (MBF) and 90% mass burn fraction (MBF) and combustion duration. MBF 10% was considered as start of combustion (SOC) and MBF 90% was considered as end of combustion (EOC). Combustion duration was taken as the difference between MBF 90% and MBF 10%. Cumulative heat release divided by total energy content of the trapped charge is called mass burned fraction [24]. This figure shows that 10% fuel burned earlier for biodiesel. This is due to the earlier start of combustion of JB100. JB100 takes lesser time for 90% of combustion as compared to mineral diesel. Combustion duration was observed slightly lower for JB100 compared to mineral diesel for 60% and 80% engine load conditions. It was mainly attributed to the higher oxygen content of biodiesel compared to mineral diesel

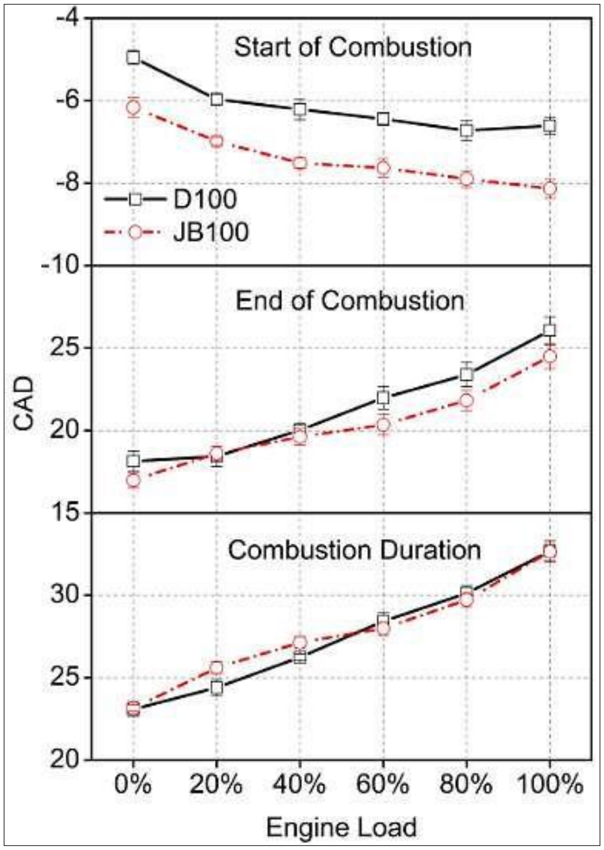


Fig. 8: Variation in mass burn fraction with engine load

IV. CONCLUSIONS

- Viscosity of biodiesel (JB100) was found to be within limit specified by ASTM D445 (1.9 to 6 mm^2/s). Density of biodiesel (JB100) was higher compared to mineral diesel. Flash point temperature for JB100 was found to be significantly higher than that of mineral diesel, suggesting that biodiesel fuels are comparatively safer to handle. Calorific value of biodiesel (JB100) was found to be lower compared to mineral diesel (D100).
- JB100 observed slightly lower CO emission compared to mineral diesel at all engine loads. Biodiesel (JB100) emitted slightly lower HC and NOx emission compared to mineral diesel at all engine loads but the difference was very small. Smoke opacity was higher for JB100 compared to mineral diesel.
- Biodiesel (JB100) showed slightly higher in-cylinder pressure compared to mineral diesel at higher engine loads. HRR_{max} observed lower for JB100 compared to mineral diesel (D100). Combustion duration observed lower for biodiesel (JB100) compared to mineral diesel for 60% and 80% of engine load conditions. It was mainly attributed to the higher oxygen content of biodiesel compared to mineral diesel. But combustion duration was slightly higher for JB100 at 20% and 40% of the engine load conditions.

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