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Emission and Combustion Characteristics of Vegetable Oil (*Jatropha curcus*) Blends in an Indirect Injection Transportation Engine

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Abstract *– The scarce and rapidly depleting conventional petroleum resources have promoted research for alternative fuels for internal combustion engines. Among various possible options, fuels derived from vegetable oils present promising "greener" substitutes for fossil fuels. Vegetable oils due to their agricultural origin are able to reduce net* CO_2 *emissions to the atmosphere along with import substitution of petroleum products. However, several operational and durability problems of using straight vegetable oils in diesel engines are reported, which are because of their higher viscosity and low volatility compared to mineral diesel. In the present research, an experiment was designed to study the effect of reducing Jatropha oil's viscosity by blending it with mineral diesel, thereby eliminating its effect on combustion characteristics of the engine. In the present experimental research, vegetable oil (Jatropha curcus) was used as substitute fuel. Experimental investigations have been carried out to examine the emission and combustion characteristics of an indirect injection transportation diesel engine running with mineral diesel and vegetable oil blends. Engine tests were performed at different engine loads ranging from no load to 100% rated load at a constant engine speed (2000 rpm). A careful analysis of engine emissions, cylinder pressure rise, instantaneous heat release and cumulative heat release was carried out vis-à-vis mineral diesel to find the suitability of Jatropha oil blends in an unmodified IDI medium duty transportation diesel engine.*

Keywords – Blending, combustion characteristics, *Jatropha curcus*, pressure-crank angle diagram, rate of heat release.

1. INTRODUCTION

Biofuels appear to be a potential alternative "greener" energy substitute for fossil fuels. These are renewable and available throughout the world. The sulphur content is negligibly small thus the issue of acid rain is therefore, ameliorated. The problem of using neat vegetable oils in diesel engines relates to their high viscosity. Researchers reported that using raw vegetable oils in the diesel engines can cause numerous engine-related problems [1]. High viscosity and low volatility of these oils cause to severe engine deposits, injector coking, and piston ring sticking [2], [3]. Hundred percent vegetable oils cannot be used safely in a DI diesel engine. The problems of high fuel viscosity can be overcome by converting the oil into primary esters, blending with conventional fuels, and heating [4]. Vegetable oils exhibit longer combustion duration with moderate rates of pressure rise, unlike petroleum derived fuels [5], [6]. Some researchers reported that the jet penetration rates of vegetable oil spray increased and cone angle decreased as the viscosity reduced by increasing the temperature of the oils [7]–[9]. Vegetable oils and their derivatives in diesel engines lead to substantial reduction in emissions of sulfur oxides, carbon monoxide (CO), poly aromatic hydrocarbons (PAH), smoke, particulate matter (PM) and noise. Furthermore, 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 [10]–[12]. Vegetable oils can be used directly or blended with mineral diesel to operate compression ignition engines. Use of blends of vegetable oils with mineral diesel have been experimented with success by various researchers in several countries [13]. Caterpillar (Brazil) used pre-combustion chamber engines with a blend of 10% vegetable oil while maintaining same power output without any engine modifications [14]. It has been reported that use of 100% vegetable oil is also possible with fuel system modifications [15]. Short-term engine performance tests have indicated good potential for most vegetable oils as fuel. The use of vegetable oils results in increased volumetric fuel consumption and brake specific fuel consumption (BSFC). Emissions of CO, HC and SO_x were found to be higher, whereas NOx and particulate emission were lower compared to diesel [13], [16], [17]. Some studies reported lower exhaust emissions including PAHs and PM [15], [18]. High viscosity of vegetable oils (30–200 cSt @ 40^0C) as compared to mineral diesel (4cSt @ 40^0C) lead to unsuitable pumping and fuel spray characteristics. Larger size fuel droplets are injected from injector nozzle instead of a spray of fine droplets, leading to inadequate air-fuel mixing. Poor atomization, lower volatility, and inefficient mixing of fuel with air contribute to incomplete combustion. This results in an increase in higher particulate emissions, combustion chamber deposits, gum formation and unburned fuel in the lubricating oil.

Pramanik *et al.* [7] found that 50% blend of Jatropha oil can be used in diesel engine without any major operational difficulties but further study is required for the assessment of long-term durability of the engine. Direct use of vegetable oils and/or the use of blends of the oils have generally been considered to be not satisfactory and impractical for both direct and indirect diesel engines [19]. The high viscosity, acid composition, free fatty acid content, as well as gum formation due to oxidation, polymerization during storage and combustion, carbon

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deposits and lubricating oil thickening are obvious problems [20]–[22]. Bari *et. al.* [19] observed the combustion characteristics of crude palm oil (CPO) and found 6% higher peak pressure than diesel. It was also observed that CPO had a 2.6^0 shorter ignition delay but lower maximum heat release rate compared with diesel. Palm oil consists of roughly 50% saturated and 50% unsaturated fatty acids. Chemical reactions, such as cracking of the double bond of the carbon chain, could have produced light volatile compounds, which result in a shorter ignition delay compared with diesel. Due to shorter ignition delay, less fuel is injected during the delay period resulting in lower maximum heat release rates. This also results in less intense premixed combustion, and usually translates into lower tendency to knock. CPO had a longer combustion period than diesel. This is due to the fact that another chemical reaction, polymerization of vegetable oil at the high temperature spray core, could have produced heavy low-volatility compounds. These heavy compounds are difficult to combust and could not completely burn in the main combustion phase, and subsequently continued to burn in the late combustion phase. Kalam *et al.* [23] reported that the addition of 30% COCO with diesel produced higher brake power and net heat release rate with a net reduction in exhaust emissions such as HC, NO_x, CO, smoke and polycyclic aromatic hydrocarbon (PAH). 40 and 50% COCO blends, developed lower brake power and net heat release rate due to fuel's lower calorific value; nevertheless, reduced emissions were also observed. Thus, neat vegetable oils are not viable options at present, but their addition to diesel fuel in low concentrations can be considered as equivalent to oxygenated fuel additives, of course with the added advantage of renewability and CO_2 emission reduction.

In the present experimental study, the emission and combustion behavior of vegetable (*Jatropha Curcus*) oil blends (V05, V10, V20 and V50) at different engine torque (no load to 100% rated load) at constant engine speed (2000 rpm) is observed and compared to the base line data of mineral diesel in an unmodified transportation indirect injection diesel engine.

2. EXPERIMENTAL SET UP AND PROCEDURE

The engine experimental setup (Figure 1) used in this work consists of a Mahindra & Mahindra (model XD-3P) four-cylinder engine coupled with an eddy current dynamometer. This is a water-cooled, indirect-injection, four-stroke, four cylinder diesel engine. The eddy-current dynamometer (Model: ASE-50; Make: Schenck Avery, India) is equipped with a dynamometer controller capable of loading the engine at any desired speed/ load combination. Detailed specifications of the engine are given in Table 1. A high speed data acquisition system (Model: Indimeter-619; Make: AVL, Austria) is used for recording and analyzing the pressure-crank angle data. A raw exhaust emission analyser (Model: EXSA-1500; Make: Horiba, Japan) is used for gaseous species measurement and smoke opacity is measured by smoke opacimeter (Model: AVL 436; Make: AVL, Austria). The properties of primary fuels used forin the experiment are given in Table 2.

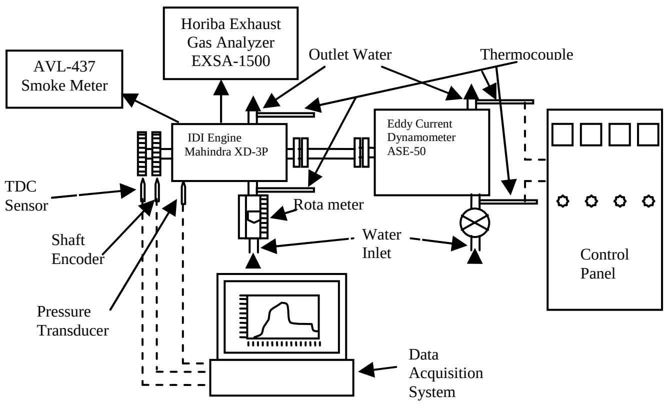

Fig. 1. Schematic diagram of experimental setup

Table 1. Technical specifications of the test engine

Model	Mahindra XD-3P
Type	water- cooled, four-stroke
Number of cylinders	4
Compression ratio	23:1
Bore/ Stroke	94 mm/90 mm
Power output	72.5 hp @4000 rpm without oil cooler
Max. torque	125 N-m @ 2000 rpm
Loading device	Eddy current dynamometer

Table 2. Various physical properties of mineral diesel and Jatropha oil

Property	Diesel	Jatropha Oil
Density (kg/m^3)	833.7	921.8
Kinematic Viscosity @ 40°C (cSt)	2.71	34.33
Flash Point (°C)	48	180
Carbon Residue %, (w/w)	0.08	0.74
Ash Content %, (w/w)	0.014	0.036
Carbon %, (w/w)	82.12	76.56
Hydrogen %, (w/w)	14.72	13.19
Nitrogen %, (w/w)	1.45	0.34
Copper Corrosion	Class 1	-

The following parameters were acquired/calculated for emission and combustion characteristics analysis from the engine experimental setup.

Emissions

(a) Total Hydrocarbon (THC)
(b) Carbon- monoxide (CO)
(c) Oxide of Nitrogen (NO_x)
(d) Carbon -dioxide (CO_2)
(e) Smoke Opacity

The raw emissions from the Horiba raw exhaust gas emission analyzer were converted to mass emission using IS-14273 code.

Combustion Characteristics

(a) Pressure crank angle diagram
(b) Instantaneous heat release rates
(c) Cumulative heat release rates
(d) Rate of pressure rise
(e) Mass fraction burned
(f) Combustion duration

3. RESULTS AND DISCUSSIONS

Emission Results

a) Total hydrocarbon emission

The total hydrocarbon mass emissiond are reported in Figure 2 for various vegetable oil blend vis-a-vis mineral diesel. It is very clear that vegetable oil blends emit lower THC at lower engine loads.

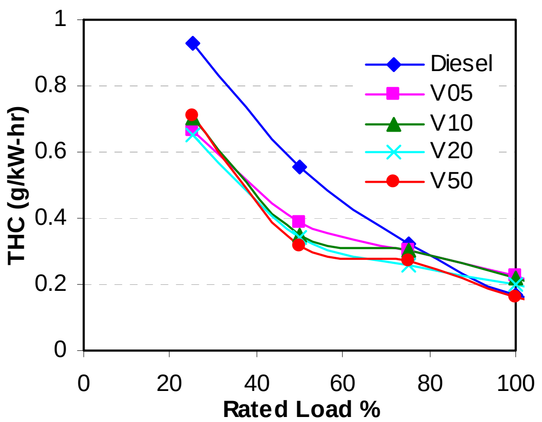

Fig. 2. THC emissions from different jatropha oil blends

At higher engine loads, the HC mass emission stabilizes due to richer combustion and lower availability of oxygen due to relatively richer F/A mixture.

b) Carbon- monoxide Emission

Figures 3 show the comparison of the CO emissions from different blends at different engine loads.

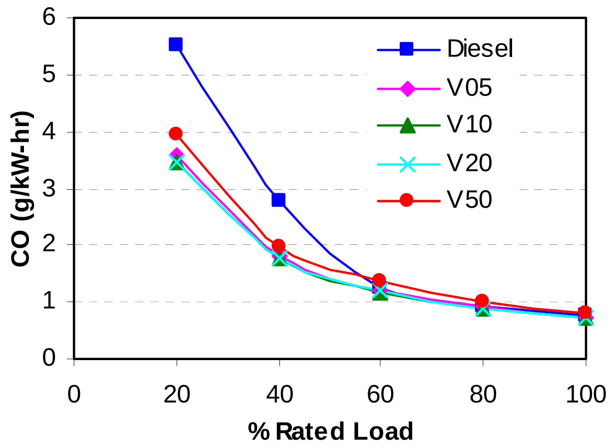

Fig. 3. Carbon monoxide emissions from different Jatropha oil blends

Figure 3, for vegetable oil blends, shows lesser CO emissions in comparison to diesel at lower engine loads. As the engine load increases, CO mass emissions go down for all fuel blends. As the engine operates at full load, the temperature in the cylinder of engine increases, which improves the atomization/vaporization of vegetable oils blends thus preparing a better and more homogenous air/fuel mixture and an improved combustion is achieved.

c) NO_x emission

The mechanism of NO_x formation has been studied extensively and it is accepted that it is highly dependent upon temperature, due to the high activation energy needed for the reactions involved. Hence the most significant factor that causes NO_x formation is high combustion temperatures. Nitrogen oxides (NO_x) mass emissions during test are shown in Figure 4 for various blends of vegetable oil vis-à-vis mineral diesel.

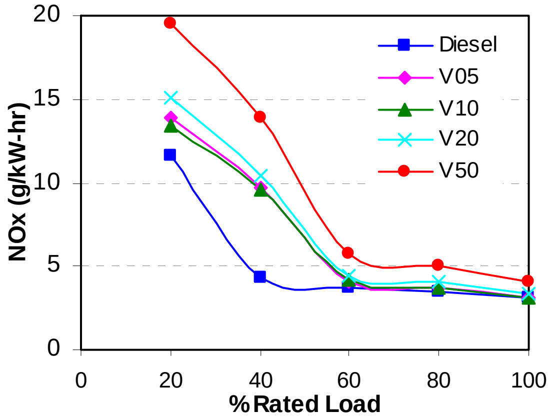

Fig. 4. NO_x emission from different Jatropha oil blends

An overall decrease in NO_x mass emissions can be observed with engine load increase. This is probably due to increase in turbulence with increase in load inside the cylinder, which contributes to a faster combustion and to lower residence time of the species in the high temperature zone. As shown in Figure 4, blends of vegetable oil produced higher NO_x than mineral diesel, which has been reported by other researchers as well [24]–[26]. The presence of oxygen in the fuel molecules may be responsible for this.

d) CO_2 emission

Figure 5 shows the CO_2 emissions from various fuel blends of vegetable oil and mineral diesel.

As the engine load increases, the emission of CO_2 also increases. The emissions of CO_2 increases as the viscosity of the fuel increases. Increase in viscosity results in decrease in spray cone angle, which leads to reduction in the amount of air entrainment in the fuel spray. This is possibly affecting combustion characteristics of the fuel.

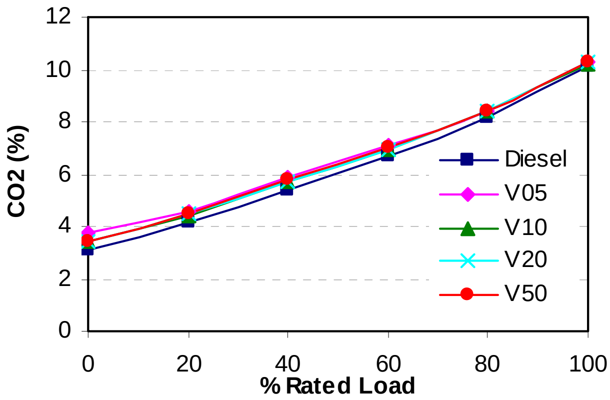

Fig. 5. CO_2 emissions from different Jatropha oil blends

e) Smoke opacity

The smoke from the IDI engine using vegetable oil and its blends with mineral diesel is shown in Figure 6.

Smoke opacity for Jatropha oil blends (Figure 6) was higher than that of diesel. Blend V20 and V50 shows maximum opacity at higher engine loads. The greater smoke opacity percentages of vegetable oil fuels are mainly due to larger carbon chain length fuel molecules, which do not get enough time to burn completely in the combustion chamber.

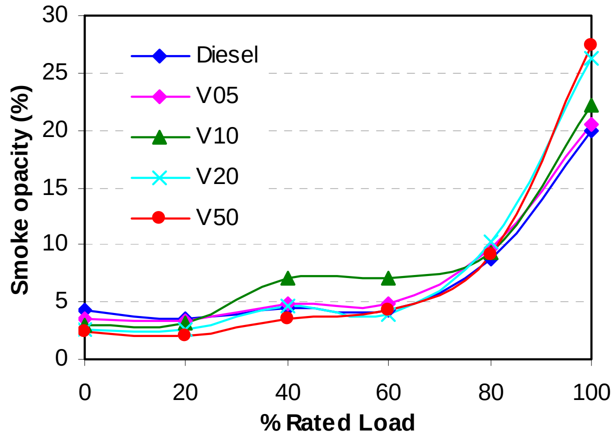

Fig. 6. Smoke opacity from different Jatropha oil blends

Combustion Characteristics

a) In-cylinder pressure vs. crank angle diagrams

Measurement of engine cylinder pressure is very important tool for understanding the process of combustion. Measurement of cylinder pressure provides sufficient information for combustion analysis and determination of reliable statistical data that can not be measured directly (heat release, mass fraction burned, pressure-volume, etc.). In IDI engine, combustion starts in the auxiliary chamber; the pressure rise associated with combustion forces hot combusting gases back into the main chamber, where these burning gases entrain and mix with the main chamber air, and all hydrocarbon fuel burns out (110 to 150 ATDC).The P-θ diagram for different vegetable oil blends at two different engine loads is shown in Figure 7. For jatropha oil blends (V20, V50) peak pressure is found to be higher than other blends/diesel at no load condition (Figure 7a).

Peak cylinder pressure increases as the proportion of vegetable oil in the blends is increased. At all engine loads, combustion starts earlier for vegetable oil blends compared to mineral diesel. As the engine load is increased, combustion start point comes closer for all fuels. Ignition delay for all fuels decreases as engine load increases because residual gas temperature inside the cylinder is higher at high engine loads, which reduces the physical ignition delay. A secondary peak was noticed (Figure 7b) at 100% rated engine loads for both, blends of vegetable oil as well as diesel. Peak pressure is higher for vegetable oil blends at low engine load (Figure 7a) but at higher engine load, peak pressure of vegetable oil blends was reported to be closer to mineral diesel (Figure 7b).

Maximum cylinder pressure for different blends at different engine loads is shown in Figure 8 for vegetable oil blends. At lower loads (Figure 8), the peak cylinder pressure is higher in vegetable oil blends. Normally as engine load increases, the cylinder pressure increases, for direct injection diesel engine. In the present investigations, (maximum cylinder pressure of IDI engine) the maximum cylinder pressure goes down at intermediate engine loads and then again rises at higher engine loads (Figure 8).

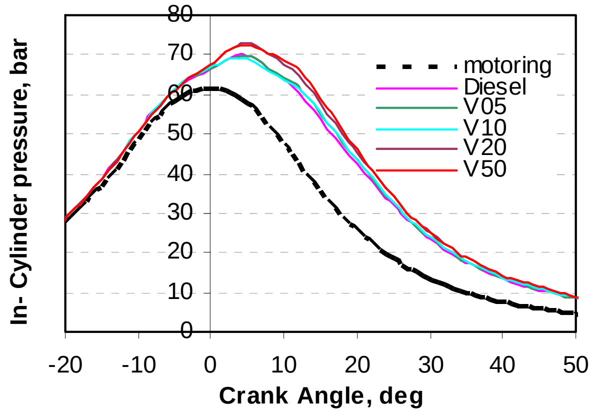

Fig. 7a. Pressure crank angle diagram for vegetable oil blends, at no load @ 2000rpm

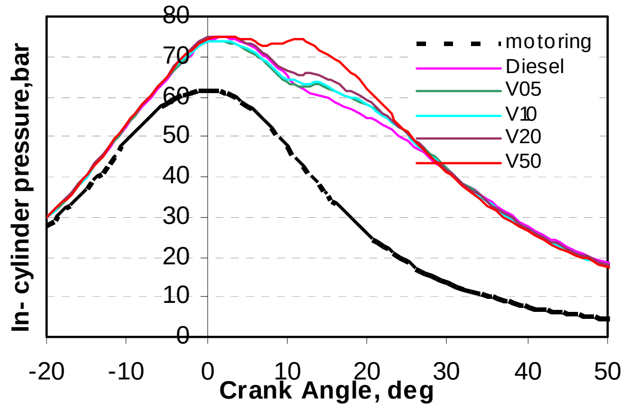

Fig. 7b. Pressure crank angle diagram for vegetable oil blends at 100% load, 125N-m torque @2000 rpm

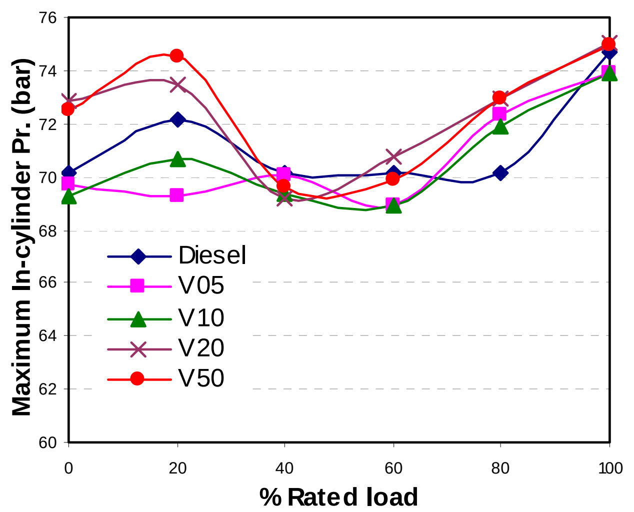

Fig. 8. Maximum cylinder pressure at 2000 rpm for Jatropha oil blends and diesel

Figure 9 shows the crank angle (aTDC) at which peak cylinder pressure occurs for all blends at different engine operating conditions. Figure shows that peak cylinder pressure for vegetable oil blends occurs in the range of 1-5^0 aTDC.

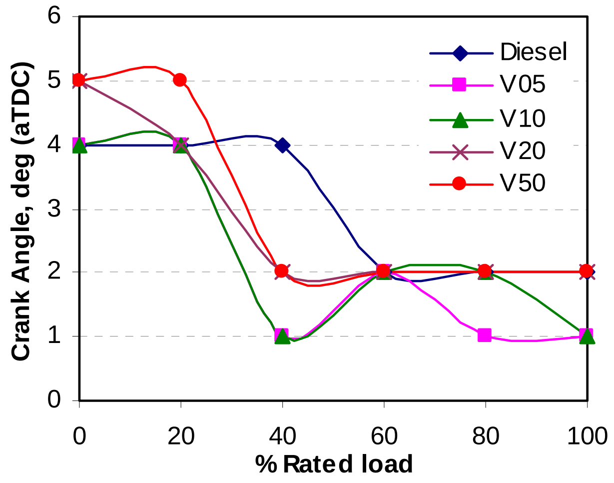

Fig. 9. Peak pressure crank angle (aTDC) for vegetable oil blends

As shown in Figures 8 and 9, the peak cylinder pressure shifts towards TDC as engine load increases. Figure 9 shows that peak cylinder pressure occurs relatively later in vegetable oil blends at low engine loads. However at higher engine loads, peak pressure occurs earlier, closer to TDC for all fuels. At higher engine loads, ignition delay become shorter for vegetable oil blends. Therefore premixed combustion phase shifts closer to TDC.

b) Rate of cylinder pressure rise

The rate of pressure rise is a very important parameter, which determines smooth functioning of the engine as well as smother transfer of gas pressure forces to mechanical linkages. The rate of cylinder pressure rise with crank-angle is shown in Figure 10 for vegetable oil blends.

As shown in Figure 10, the first peak of pressure gradient shows the start of combustion. The second small peak is due to mixing controlled combustion phase. As the engine load increases, this phase moves closer to TDC. The first peak represent premixed combustion phase and the second peak is due to mixing controlled combustion phase.

At higher engine loads, another peak appears near 10^{0}aTDC representing the late combustion phase. Since heavier molecules of vegetable oils take longer time to burn compared to mineral diesel. The maximum rate of cylinder pressure rise, if above a certain limit, gives rise to jerky engine operation and poses danger of failure of engine components used in the powertrain.

Figure 11 shows maximum rate of pressure rise for vegetable oil blends and diesel. Figure 11 shows that as engine load increases, the rate of pressure rise increases for vegetable oil blends. This is possibly due to higher amount of fuel being injected and burned with increase in engine load.

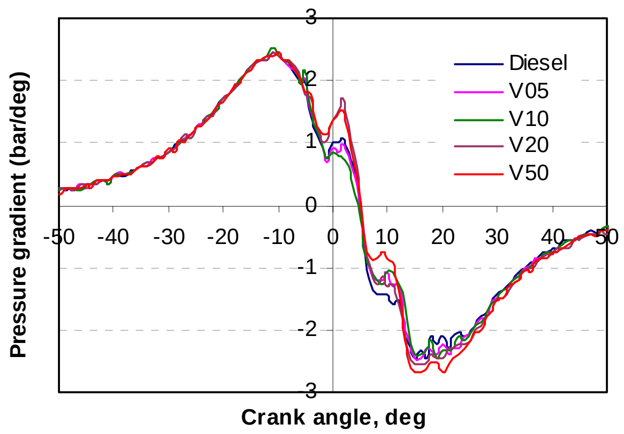

Fig. 10a. Rate of cylinder pressure rise at no load for vegetable oil blends

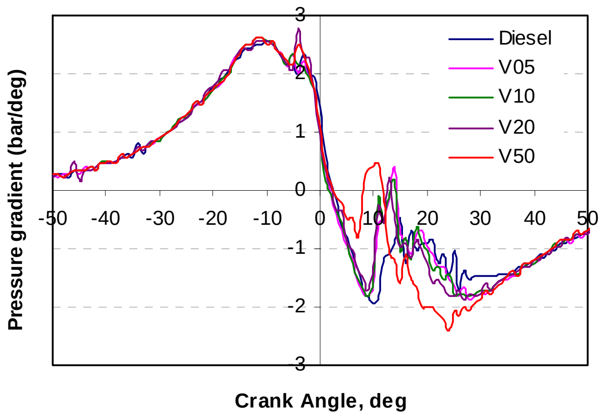

Fig. 10b. Rate of cylinder pressure rise at 100% load for vegetable oil blends

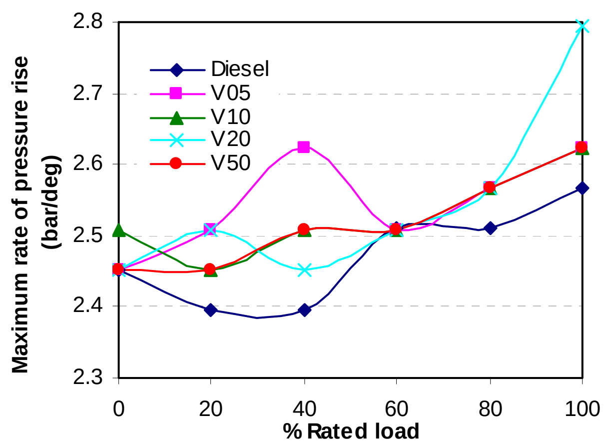

Fig. 11. Maximum rate of pressure rise for vegetable oil blends

c) Instantaneous heat release

The details about combustion stages and events can often be determined by analyzing apparent heat release rates as determined from cylinder pressure history. Figures 12a and 12b show the instantaneous heat release rates. The two peaks in heat release rates are normally associated with premixed and mixing-controlled combustion. The premixed combustion starts from the start of heat release up to the end of premixed burn phase. It is observed from Figure 12 that the ignition delay period was shorter for vegetable oils and the premixed combustion phase for diesel was longer and more pronounced owing to relatively longer delay of the diesel (Figure 12b). The mixing-controlled combustion phase, which largely depends on the mixing of air and fuel, was similar in nature for diesel and vegetable oil blends. Combustion starts earlier for vegetable oil blends partially due to shorter ignition delay and partially due to advanced injection timing (because of higher bulk modulus and higher density of vegetable oils).

Figure 12 shows the instantaneous heat release for vegetable oil blends. The premixed combustion phase for all vegetable oil blends shift towards TDC and also the magnitude of premixed combustion phase for all fuel blends reduce with engine load increase. This is because in IDI engine, the mixing of fuel takes place in the pre-combustion chamber, after which the charge is thrown in to the main combustion chamber violently through the nozzle. As the load increases, more amount of fuel is injected into the pre-combustion chamber and richer fuel-air mixing takes place, before throwing this rich heterogeneous charge into main chamber. Due to this effect, the heat release in premixed combustion phase reduces and the combustion of fuels is mainly dominated by mixing controlled combustion phase. Vegetable oils do not burn as quickly in pre-chamber and the burning fuel-air mixture mainly takes place in the main combustion chamber, where mixing–controlled combustion dominates.

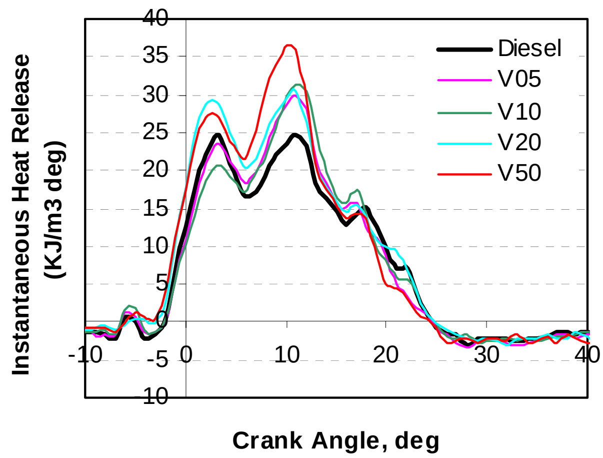

Fig. 12a. Instantaneous heat release for vegetable oil blends, at no load @ 2000rpm

The start of fuel injection for the vegetable oil blends occur earlier than diesel fuel. This is probably due to a combination of the different physical properties of the fuel and fuel quantity-related changes in the injection pump. The combination of earlier injection and shorter ignition delay causes the vegetable oil blends to ignite earlier than diesel fuel. Since the delay is shorter for vegetable oil; the premixed combustion phase for diesel fuel is found to be longer and more pronounced owing to longer delay of diesel. The mixing-controlled combustion phase, which largely depends on the mixing of air and fuel, was similar in nature for diesel and vegetable oil blends. However, the heat release during the late combustion phase for vegetable oil blends was marginally higher than that for diesel. Vegetable oil constituents have higher boiling points than diesel. These constituents with higher boiling point do not get adequately evaporated during the mixing-controlled combustion phase and continue to burn in late combustion phase.

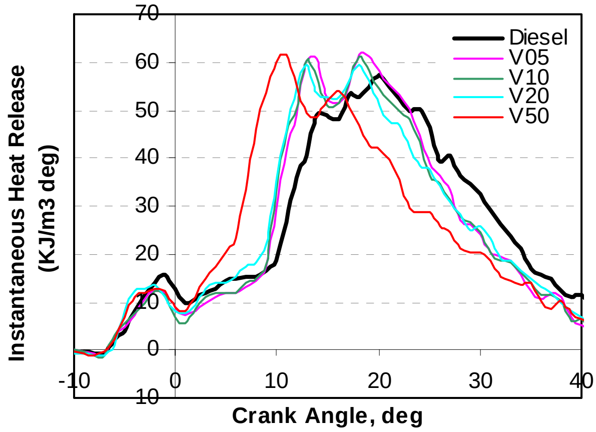

Fig. 12b. Instantaneous heat release for vegetable oil blend, at 100% load, 125N-m torque @2000 rpm

(d) Cumulative heat release

The cumulative heat release curves were obtained by integrating the instantaneous rate of heat release curves (Figure 12). This gives information about how much fuel was unburned at any given point in the combustion cycle. Representative curves for cumulative heat release from the fuel with respect to crank angle at 2000 rpm and different engine loads are shown in Figure 13, for various vegetable oil blends. These figures show a tendency of earlier heat release for vegetable oil blends, which becomes more prominent at higher engine loads. Combustion of mineral diesel fuel starts later but quickly it exceeds cumulative heat release for vegetable oil blends, suggesting faster burn rate of mineral diesel. As shown in Figure 13, the heat releases earlier for vegetable oil blends at any particular crank angle. It becomes more prominent at higher crank angles. Crank angle duration from 5% mass burn to 90% mass burn has been calculated to compare combustion duration for different fuels. Vegetable oil are oxygenated fuels and in IDI engine, better mixing of air-fuel takes place due to swirling of air in pre-combustion chamber hence the effect of viscosity has lower impact on combustion duration. It is possibly due to shorter ignition delay and increased fuel injection pressure.

Figures 14 show the crank angle for 5% mass fraction burned. The crank angle duration for 5% mass fraction burned at different engine operating conditions in vegetable oil blends are compared with mineral diesel. Figure 14 shows that 5% fuel burns later for vegetable oil blends possibly due to its higher fuel viscosity and inadequate mixing with air.

Figure 15 shows the crank angle for 90% fuel mass fraction burned. 90% fuel mass fraction burn duration increases with increasing engine load because higher fuel quantity needs to be injected for higher engine loads. Figure 15 suggests that 90% mass fraction burns earlier for mineral diesel, because of faster rate of heat release, and faster burn rate for mineral diesel compared to vegetable oil blends.

Vegetable oil blends have lower volatility and higher flash point in comparison to mineral diesel, which causes slower burning of vegetable oil blends. Higher volume of fuel is injected in the case of vegetable oil blends because of their lower calorific value compared to mineral diesel.

Combustion duration is regarded as the crank angle interval between 5% and 90% fuel mass burn. Figure 16 show the combustion duration for vegetable oil blends compared with base line data of mineral diesel.

At lower engine loads the combustion duration of higher vegetable oil blend (V50) is higher than that of mineral diesel because of its higher density. As the load increases, the combustion duration of vegetable oil blends come closer to mineral diesel.

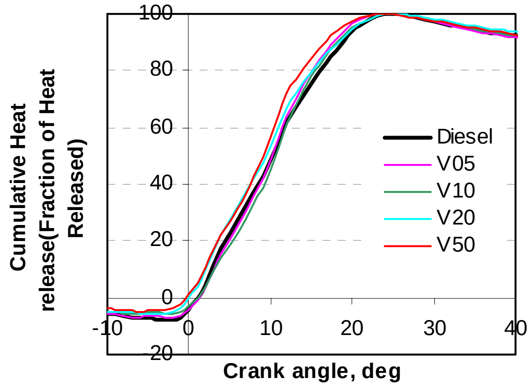

Fig. 13a. Cumulative heat release for vegetable oil blends, at no load @ 2000rpm.

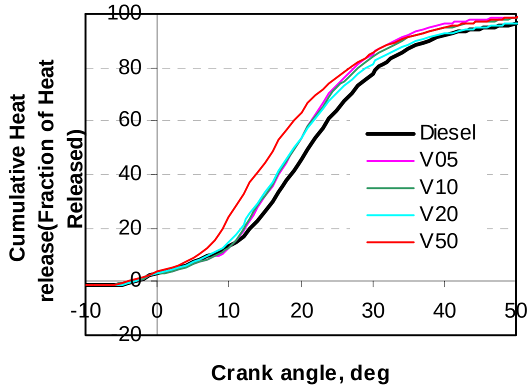

Fig. 13b. Cumulative heat release for vegetable oil blends, at 100% load, 125N-m torque @2000 rpm

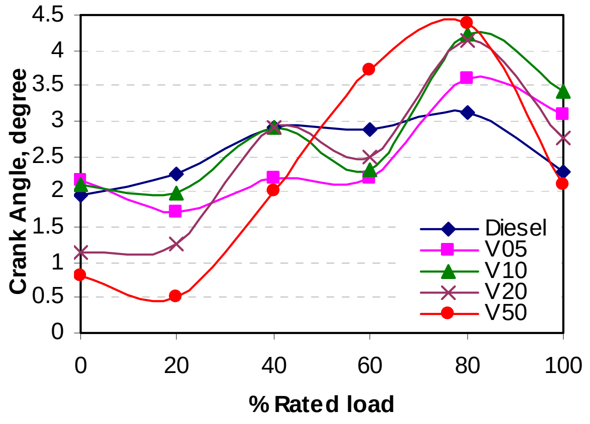

Fig. 14. Crank angle degree for 5% fuel mass burning at 2000 rpm for vegetable oil blends

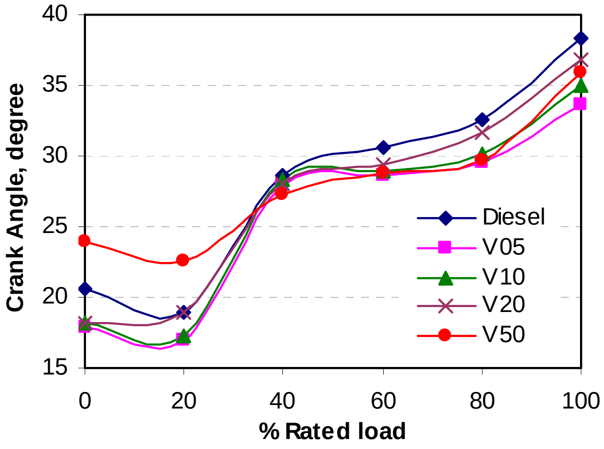

Fig. 15. Crank angle degree for 90% fuel mass burning at 2000 rpm for vegetable oil blends

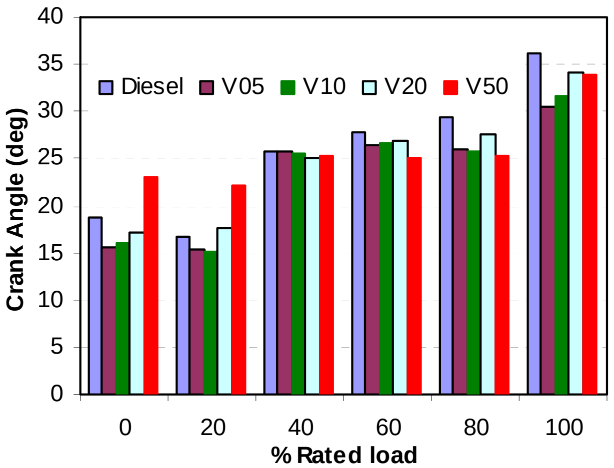

Fig. 16. Variation in combustion duration at 2000 rpm for vegetable oil blends

4. CONCLUSIONS

An indirect injection transportation diesel engine was operated under steady state, at different engine loads at constant speed (2000 rpm) to investigate the emission and combustion characteristics of Jatropha oil blends with baseline diesel. THC and CO emissions were lower for vegetable oil blends at lower engine loads. As engine load increases, the level of emission comes closer to mineral diesel. Smoke opacity and CO_2, were higher for vegetable oil blends compared to mineral diesel. Mass emission of NO_x increases with increasing vegetable oil concentration in blends. Smoke opacity of vegetable oil blends is higher than mineral diesel. At all engine operating conditions, vegetable oil blends had lower heat release rate compared to mineral diesel during premixed combustion phase. It also showed that under all engine operating conditions, start of heat release always takes place earlier for vegetable oil blends compared to mineral diesel. Combustion starts further earlier as the concentration of vegetable oil in the blend is increased. Combustion duration is observed to be similar for vegetable oil blends compared to mineral diesel. However, cylinder pressure rise for all vegetable oil was found to be higher than mineral diesel and a stable and smother engine operation was observed with vegetable oil blends. Hence it can be concluded that vegetable oil blends can be used in the engine without any hardware modification and no undesirable combustion features were observed. It can be seen that vegetable oil blends show combustion characteristics almost identical to diesel. Therefore vegetable oil blended diesel fuels can be used in compression ignition engines for transportation, however long – term endurance test need to be carried out to investigate associated durability issues.

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