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Combustion Characteristics of Jatropha Oil Blends in a Transportation Engine

Harish Kumar Gangwar, Avinash Kumar Agarwal*
Engine Research Laboratory,
Department of Mechanical Engineering,
Indian Institute of Technology Kanpur, Kanpur-208016, India
*Corresponding Author: akag@iitk.ac.in

ABSTRACT

Vegetable oils are produced from numerous oil seed crops. While all vegetable oils have high energy content, most require some processing to assure safe use in internal combustion engines. Some of these oils already have been evaluated as substitutes for diesel fuels. However, several operational and durability problems of using straight vegetable oils in diesel engines are reported in the literature, caused by of their higher viscosity and low volatility compared to mineral diesel. In the present research, experiments were designed to study the effect of reducing Jatropha oil's viscosity by blending it with mineral diesel and thereby eliminating the effect of high viscosity and poor volatility on combustion characteristics of the engine. Experimental investigations have been carried out to examine the combustion characteristics of an indirect injection transportation diesel engine running with diesel, and jatropha oil blends with diesel. Engine tests were performed at different engine loads ranging from no load to 100% rated load at constant engine speeds (2000 rpm). A careful analysis of cylinder pressure rise, instantaneous heat release and cumulative heat release was carried out. All test fuels exhibited similar combustion stages as diesel however jatropha oil blends showed earlier start of combustion and lower heat release during premixed combustion at all engine loads. The crank angle position of peak cylinder pressure for vegetable oil blends shifts towards top dead center compared to baseline diesel. The maximum rate of pressure rise was found to be higher for jatropha oil blends at higher engine loads.

Keywords: *Jatropha oil, Combustion characteristics, blending, rate of heat release, combustion phases.*

INTRODUCTION

Major problem associated with utilization of vegetable oils as diesel fuels is their high viscosity which is, 10–20 times greater than that of mineral diesel and their poor volatility characteristics [1-3]. Thus, although short- term tests using vegetable oils show promising results, problems appear after the engine is operated for longer periods. These include injector coking with trumpet formation, more carbon deposits and piston oil ring sticking, thickening and gelling of the engine lubricating oils [1,3-5]. To solve the problems associated with the very high viscosity of neat vegetable oils, the following methods are usually adopted: blending in small blend ratios with mineral diesel, micro-emulsification with methanol or ethanol, cracking and their transesterification into biodiesel [1,6,7]. Caterpillar (Brazil) in 1980 used pre-combustion chamber engines with a mixture of 10% vegetable oil to maintain total power without any alterations or adjustments to the engine. At that point, it was not practical to substitute 100% vegetable oil for diesel fuel, but a blend of 20% vegetable oil and 80% mineral diesel was successful. Some short-term experiments used up to a 50/50 blend ratio [8]. Pramanik [2] 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 long-term durability of the engine. Direct use of vegetable oils and/or the use of blends of the oil has generally been considered to be not satisfactory and impractical for both direct and indirect diesel engines [9]. The high viscosity, free fatty acid content, gum formation due to oxidation, polymerization during storage and combustion, carbon deposits and lubricating oil thickening are some of the obvious problems [10-15]. Bari *et al*. [16] observed that crude palm oil (CPO) had a 6% higher peak cylinder pressure than diesel during combustion. They also observed that CPO had a 2.6^0 shorter ignition delay but lower maximum heat release rate compared to mineral 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, which usually translates into lower tendency to knock. CPO had longer combustion duration than diesel. This is due to the fact that another chemical reaction, polymerization of vegetable oil in the high temperature spray core, could have produced heavy low-volatility compounds. These heavy compounds are difficult to combust and do not burn completely in the main combustion phase, and subsequently continued to burn in the late combustion phase. Kalam et al. [17] observed that 10 to 30% COCO (coconut oil) blends produce similar heat release rate as conventional diesel, although the average calorific value of COCO blends is about 6% lower than conventional diesel. This is expected because of a slight increase in the density of COCO blends result in higher ignition delay, which allows more fuel to mix within combustible limits during the delay period, hence a similar heat release rate is obtained. However, 40%COCO and 50%COCO blends show lower maximum heat release rate compared to other blends. For the above reasons, it is generally accepted that blends of standard diesel with 5%, 10%, 20% or up to 50% (by volume) vegetable oils can be used in existing diesel engines without any modifications, but there are concerns about the use of higher percentage blends that can limit the durability of various components, leading to engine malfunctioning. Thus, vegetable oils are not a viable option at present, but their addition to diesel in low concentrations can be considered equivalent to adding oxygenated fuel additives, with the added advantage of renewability and emitted CO_2 reduction. In this experimental study, the combustion behavior of vegetable (Jatropha Curcus) oil blends (V05, V10, V20 and V50) at different engine torque (no load, 10, 25, 50, 75,100 and 125 N-m) and at constant engine speed (2000 rpm) is investigated in comparison to the base line data of mineral diesel in an unmodified transportation indirect injection diesel engine.

EXPERIMENTAL APPARATUS & METHODOLOGY

Experiments were conducted on a four stroke, four-cylinder diesel engine (table 1) coupled with an eddy current dynamometer (Make: Schenck Avery, India; Model: ASE-50). The dynamometer was controlled by a dynamometer controller capable of loading the engine at desired speed/ load combination.

Cylinder pressure is measured using piezoelectric pressure transducer (Make: AVL, Austria; Model: GU21C), which is installed in the engine cylinder head. The pressure transducer was mounted flush with the main combustion chamber in the cylinder head.

Table 1: Technical Specifications of test engine

Make, Model	Mahindra and Mahindra, XD-3P
Type	water- cooled, four-stroke, indirect injection
Number of cylinders	four
Compression ratio	23:1
Bore/ stroke	94/ 90 mm
Power output	72.5 hp @4000 rpm without oil cooler
Max. torque	125 Nm @ 2000 rpm

A high precision inductive shaft encoder (Model AVL 333; Make: AVL Austria) is used for detecting crank angle rotation with a precision of 0.1 crank angle degrees (CAD). A magnetic pickup is used sending the TDC. It is mounted on a frame connected to the base of the engine. A twin channel high speed data acquisition system (Make: AVL, Austria; Model: Indimeter-619) is used for recording and analyzing the pressure crank angle data.

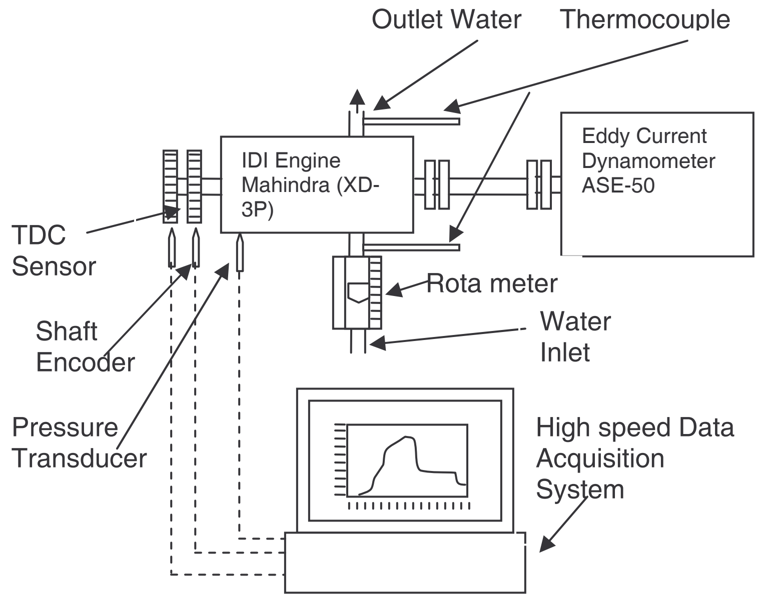

Figure 1: Schematic of Experimental setup

Several combustion parameters were analyzed from the in-cylinder pressure data such as instantaneous heat release, cumulative heat release, mass fraction burnt etc. to investigate the combustion characteristics of these fuels.

Four blends of Jatropha oil by (%v/v) and mineral diesel were tested (V5, V10, V20 and V50) in the engine. For each fuel, the engine was operated at six different torques (0, 25, 50, 75, 100, and 125 Nm) at constant speed of 2000 rpm. Main properties of jatropha and mineral diesel used for experiment are shown in table 2.

Table 2: Various Properties of Diesel and Jatropha oil

Property	Diesel	Jatropha	ASTM Test Method
Density (kg/m^3)	833.7	921.8	D 1298
Kinematic Viscosity @ 40°C (cSt)	2.71	34.33	D 6584
Flash Point (°C)	48	180	D 93
Carbon Residue%, (w/w)	0.08	0.74	D 189
Ash Content %, (w/w)	0.014	0.036	D 482
Carbon %, (w/w)	82.12	76.56	-
Hydrogen %, (w/w)	14.72	13.19	-
Nitrogen %, (w/w)	-	0.34	-
Copper Corrosion	Class 1	-	-

RESULTS AND DISCUSSION

Combustion Characteristics

A detailed experimental description of combustion evolution in diesel engines is extremely complex because of the simultaneous formation and oxidation of air/fuel mixture. Moreover, knowledge of the combustion process, even in global terms, is extremely useful if we are to better understand the mechanisms governing a greater or lesser concentration of pollutants in the exhaust gas.

A high-speed data acquisition system, a precision shaft encoder and a sensitive piezo-electric pressure transducer is used for acquiring data at a very high speed from the combustion chamber of the IDI engine using various vegetable oil blends. This data is then analyzed and presented in the form of pressure-crank angle diagrams, instantaneous heat release diagram, cumulative fuel release diagrams, rate of pressure rise, mass burn fraction diagrams, combustion duration etc.

(a) In-cylinder pressure Vs. crank angle Diagram

Measurement of engine cylinder pressure is very important tool for understanding the combustion process. Measurement of cylinder pressure provides sufficient information for combustion analysis and determination of reliable data which can not be measured directly such as heat release, mass fraction burned, pressure-volume, etc. In IDI engines, combustion first starts in the auxiliary chamber; the pressure rise associated with combustion forces fluids back into the main chamber, where the jet issuing from the nozzle entrains and mixes with the main chamber air, and main combustion of hydrocarbons (11^0 to 15^0 ATDC) takes place. The P-θ diagrams for different vegetable oil blends at various engine loads are shown in figure 2. For jatropha oil blends (V20, V50) peak pressure is found to be higher than other blends/diesel at no load conditions (Fig.2a).

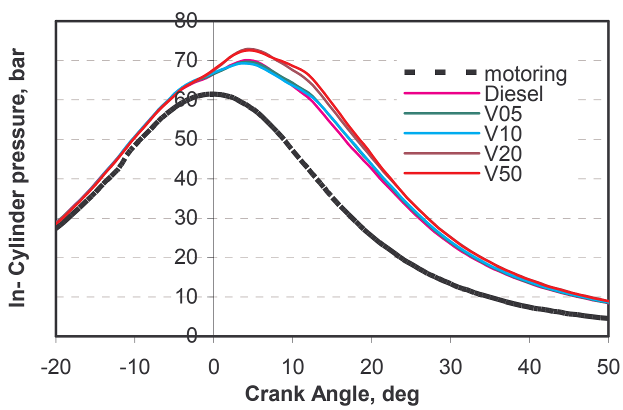

Figure 2 a: Pressure Crank Angle Diagram for vegetable oil blends, at no load @ 2000 rpm

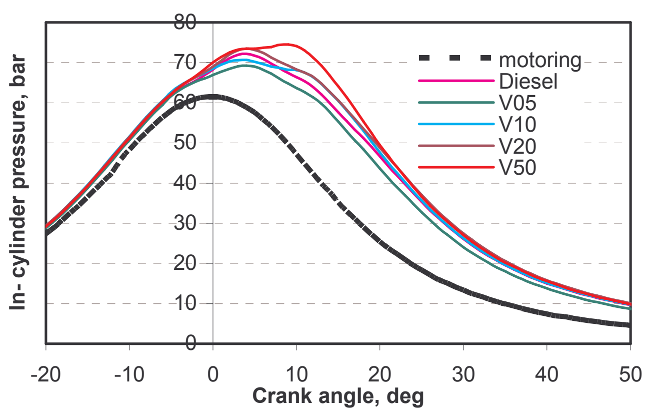

Figure 2 b: Pressure Crank Angle Diagram for vegetable oil blends at 20% load, 25N-m torque @ 2000 rpm

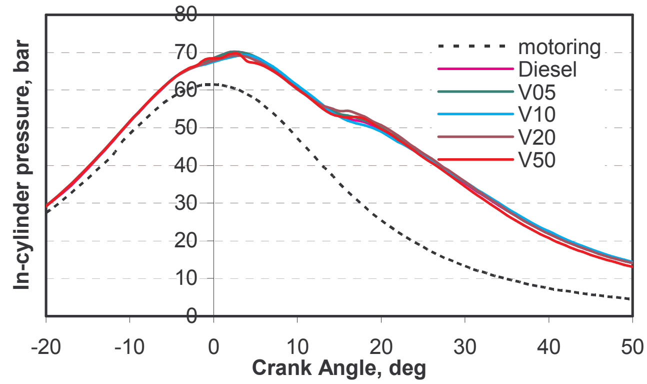

Figure 2 c: Pressure Crank Angle Diagram for vegetable oil blends, at 40% load, 50N-m torque@ 2000 rpm

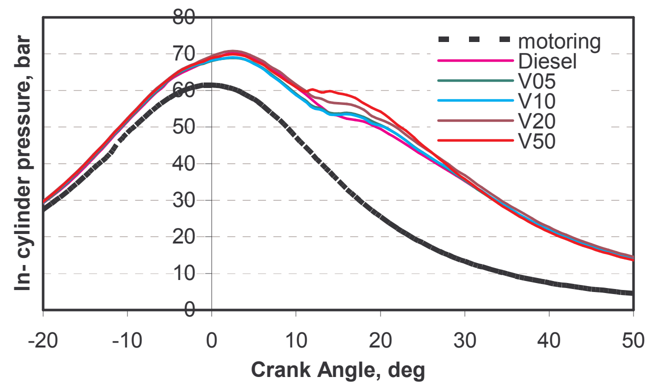

Figure 2 d: Pressure Crank Angle Diagram for vegetable oil blends at 60% load, 75N-m torque @2000rpm

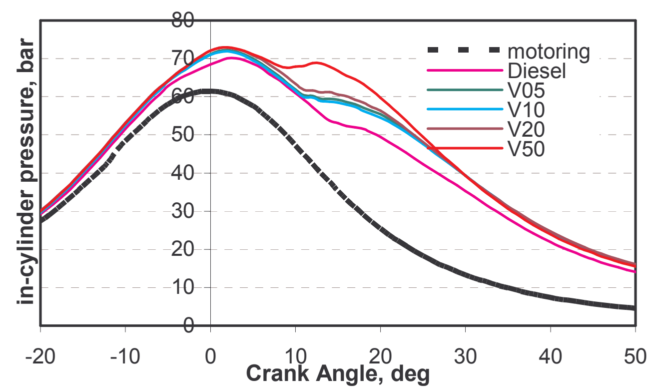

Figure 2 e: Pressure Crank Angle Diagram for vegetable oil blends, at 80% load, 100N-m torque @2000rpm

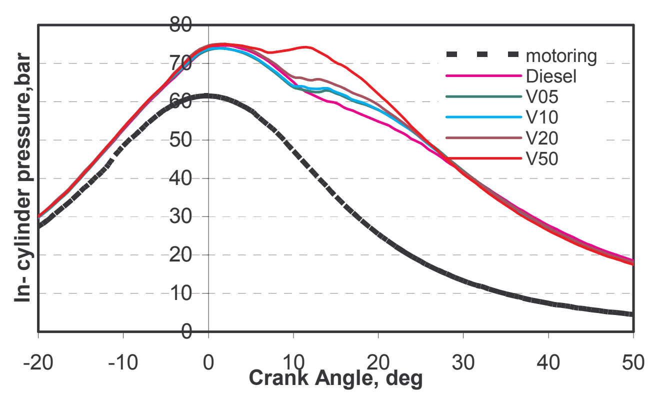

Figure 2 f: Pressure Crank Angle Diagram for vegetable oil blends at rated load, 125N-m torque@2000 rpm

Peak cylinder pressure increase as the proportion of vegetable oil in 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 (fig. 2c-f) at higher engine loads for both, blends of vegetable oil and diesel. Peak pressure is higher for vegetable oil blends at low engine load (figure 2a-c) but at higher engine load, peak pressure of vegetable oil blends was reported to be closer to mineral diesel (figure 2f).

Maximum cylinder pressure for different blends at different engine loads is shown in figure 3 for vegetable oil blends. At lower loads (fig. 3), the peak cylinder pressure is generally 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 as shown in figure 3.

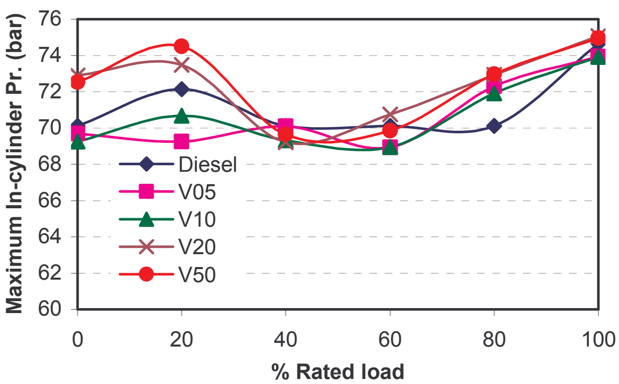

Figure 3: Maximum cylinder pressure at 2000 rpm for vegetable oil blends and diesel

Figure 4 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

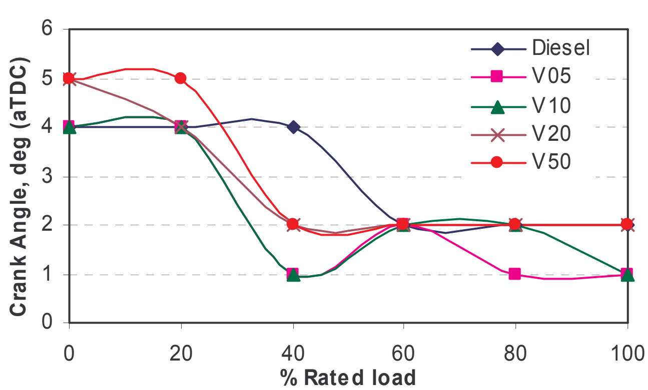

Figure 4: Peak pressure crank angle (aTDC) for vegetable oil blends

As shown in figures 3 and 4, the peak cylinder pressure shifts towards TDC as engine load increases. Figure 4 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 period 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 smoother transfer of gas pressure forces to mechanical linkages. The rate of cylinder pressure rise with crank-angle is shown in figure 5 for vegetable oil blends.

As shown in figure 5, the first peak of pressure gradient shows that start of combustion. The second small peak is due to the mixing controlled combustion phase. As the load increases, this phase comes towards TDC as shown in figures (5 b,c,d,). The first peak represent premixed combustion phase and the second one is due to mixing controlled combustion phase.

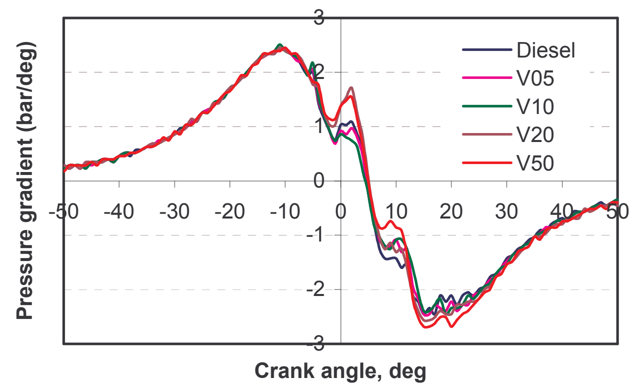

Figure 5 a: Rate of cylinder pressure rise at no load for vegetable oil blends

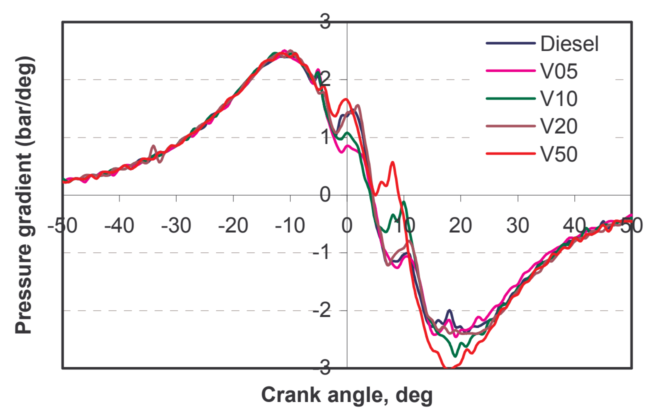

Figure 5b: Rate of cylinder pressure rise at 20% load for vegetable oil blends

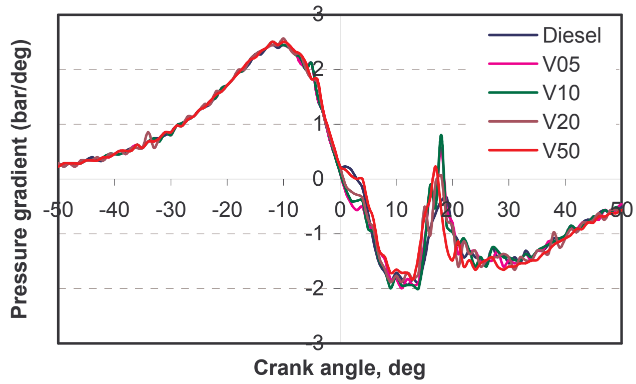

Figure 5 c: Rate of cylinder pressure rise at 40% load for vegetable oil blends

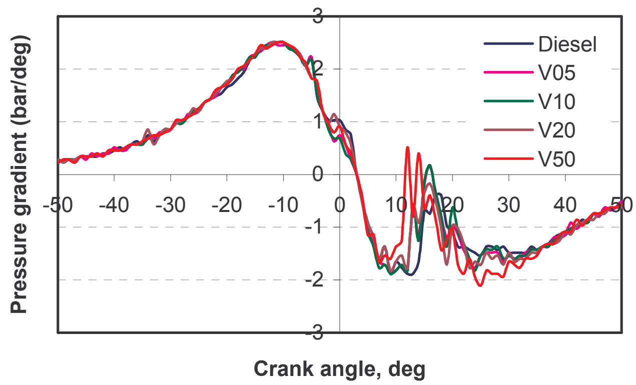

Figure 5 d: Rate of cylinder pressure rise at 60% load for vegetable oil blends

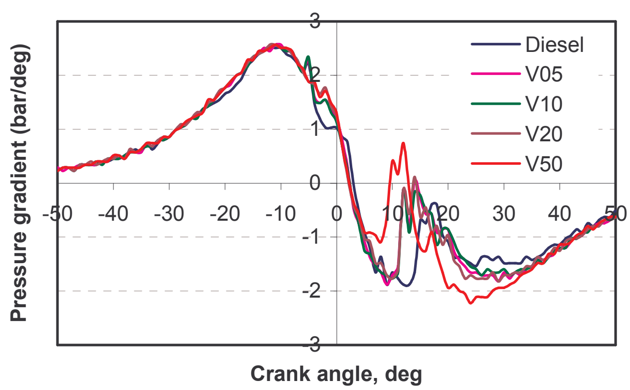

Figure 5 e: Rate of cylinder pressure rise at 80% load for vegetable oil blends

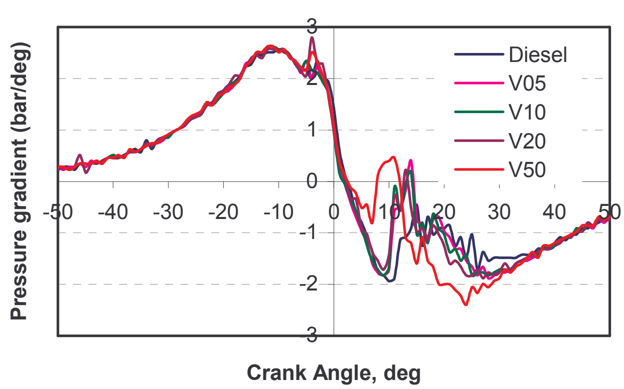

Figure 5 f: Rate of cylinder pressure rise at 100% load for vegetable oil blends

At higher engine loads, another peak appears 10^0 aTDC representing the late combustion phase. Since heavier molecules of vegetable oils, takes more 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 power-train.

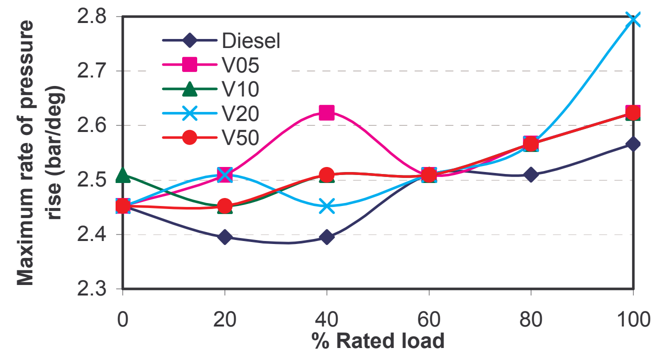

Figure 6: Max. rate of pressure rise for vegetable oil blends

Figure 6 shows maximum rate of pressure rise for vegetable oil blends and diesel. Figure 6 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.

(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 7 a-f 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 fig.7 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 (fig 7c,d,f). 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 7 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 reduces 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. Then this rich heterogeneous charge is thrown 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 pushed into the main combustion chamber, where mixing–controlled combustion dominates.

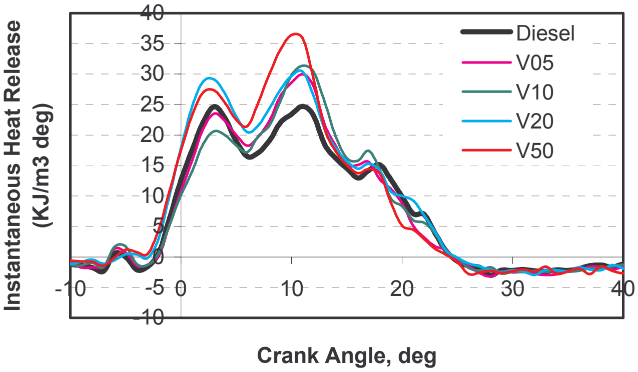

Figure 7 a: Instantaneous heat release for vegetable oil blends, at no load @ 2000rpm

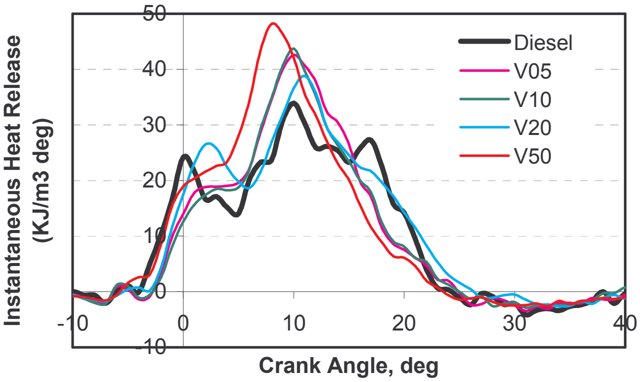

Figure 7 b: Instantaneous heat release for vegetable oil blends, at 20% load, 25N-m torque @2000 rpm

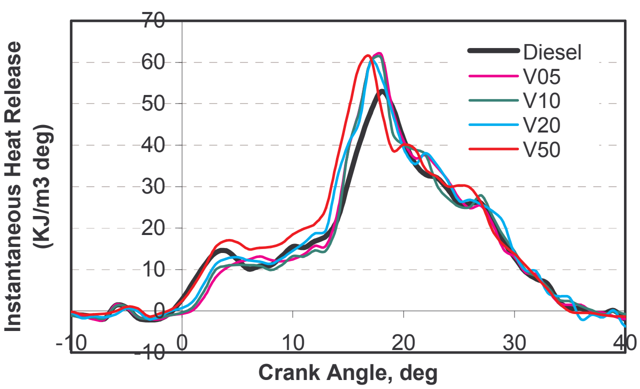

Figure 7 c: Instantaneous heat release for vegetable oil blends, at 40% load, 50N-m torque @2000 rpm

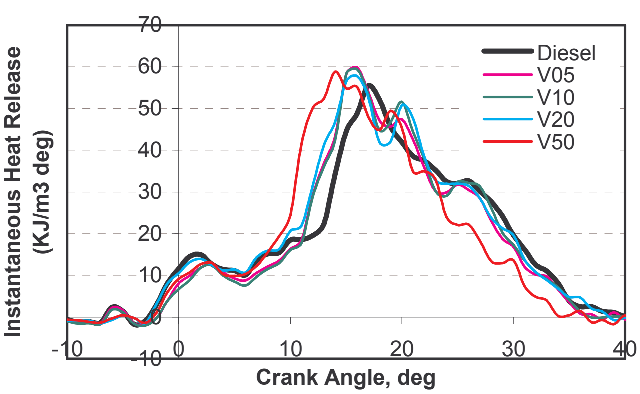

Figure 7 d: Instantaneous heat release for vegetable oil blends, at 60% load, 75N-m torque @ 2000 rpm

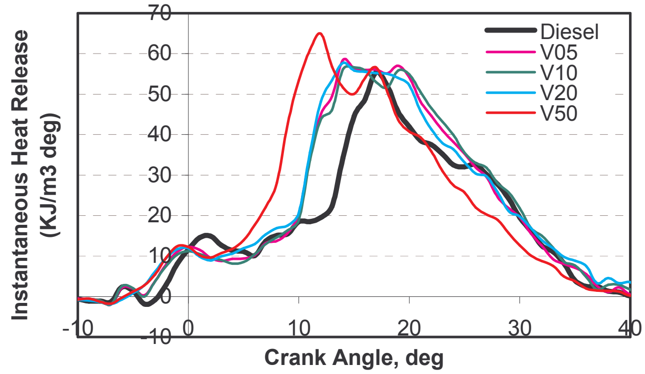

Figure 7 e: Instantaneous heat release for vegetable oil blend, at 80% load, 25N-m torque @2000rpm

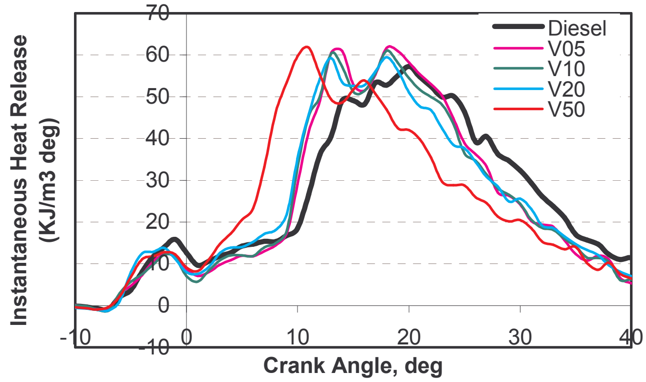

Figure 7 f: Instantaneous heat release for vegetable oil blend, at 100% load, 125N-m torque @2000 rpm

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.

(d) Cumulative heat release

The cumulative heat release curves were obtained by integrating the instantaneous rate of heat release curves (fig.7). 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 8, 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 for mineral diesel starts later but quickly it exceeds cumulative heat released for vegetable oil blends, suggesting faster burn rate of mineral diesel. As shown in figure 8, 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 found to calculate and 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 so the effect of viscosity has lower impact on combustion duration. It is possible due to shorter ignition delay and increased fuel injection pressure.

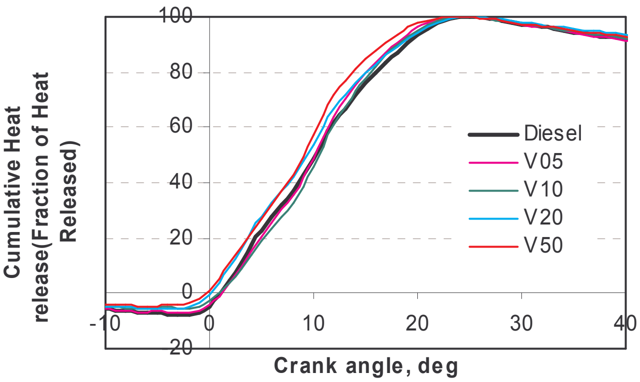

Figure 8 a: Cumulative heat release for vegetable oil blends, at no load @ 2000rpm.

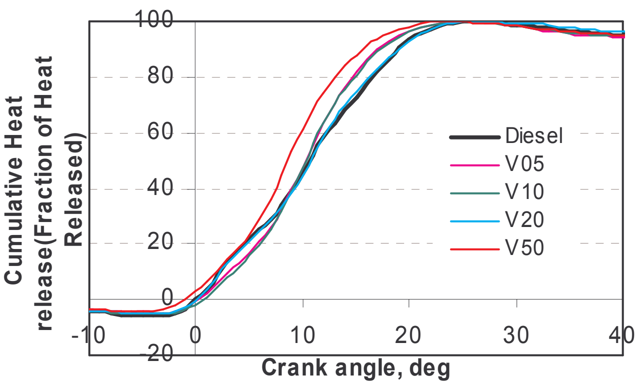

Figure 8 b: Cumulative heat release for vegetable oil blends, at 20% load, 25N-m torque @2000 rpm

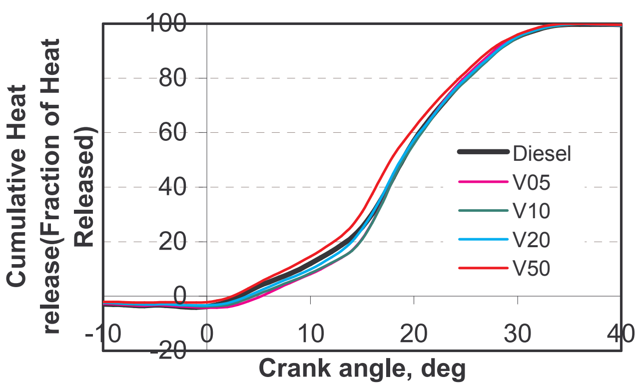

Figure 8 (c): Cumulative heat release for vegetable oil blends at, 40% load, 50N-m torque @2000 rpm

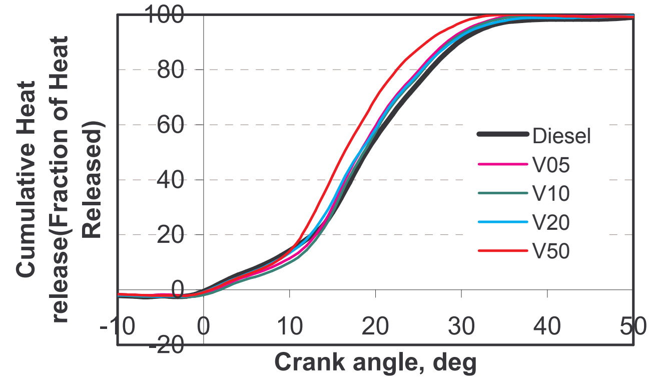

Figure 8 d: Cumulative heat release for vegetable oil blends at, 60% load, 75N-m torque @2000 rpm

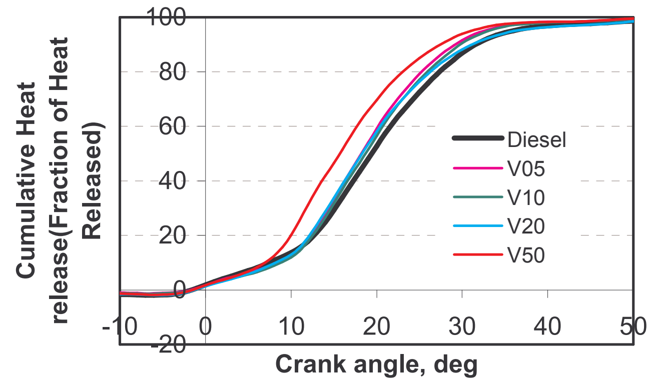

Figure 8 e: Cumulative heat release for vegetable oil blends, at 80% load, 100N-m torque @2000 rpm

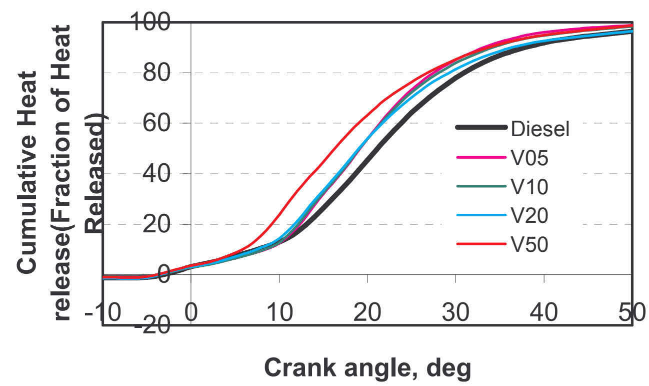

Figure 8 f: Cumulative heat release for vegetable oil blends, at 100% load, 125N-m torque @2000 rpm

Figure 9 shows the crank angle for 5% fuel 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 9 show that 5% fuel burns earlier for vegetable oil blends at lower engine loads, possibly due to lower ignition delay. 5% fuel burns later for vegetable oil blends (due to higher viscosity and lower volatility) at high engine loads. A part of the reason why this would be observed is that, at low loads, advanced ignition delay timing of vegetable oils would supersede the effect of fuel viscosity (which would be less since a small quantity of fuel is injected at low loads). This might give a faster 5% burn rate for vegetable oils at low loads as compared to diesel. But at higher loads since the ignition delay is roughly the same for all fuels, the viscosity and volatility effect would dominate since the bulk fuel injected is high which might make the vegetable oils to burn slower.

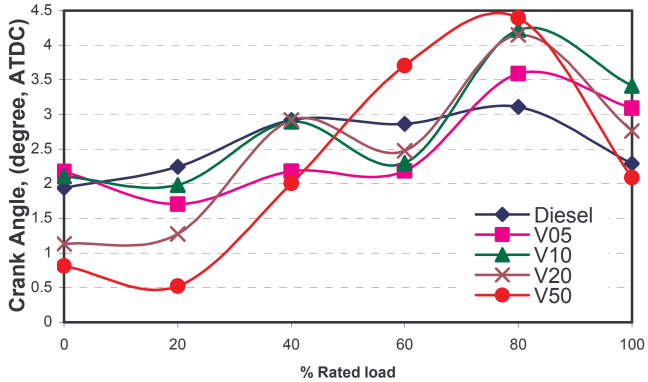

Figure 9: Crank angle degree for 5% fuel mass burning at 2000 rpm

Figure 10 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 is injected to meet higher loads. Figure 10 suggests that 90% mass fraction burns earlier for mineral diesel at lower engine loads, because of faster rate of heat release, and faster burn rate for mineral diesel in comparison to vegetable oil blends. At high engine loads, the 90% mass fraction burns later for diesel, compared to vegetable oil blends.

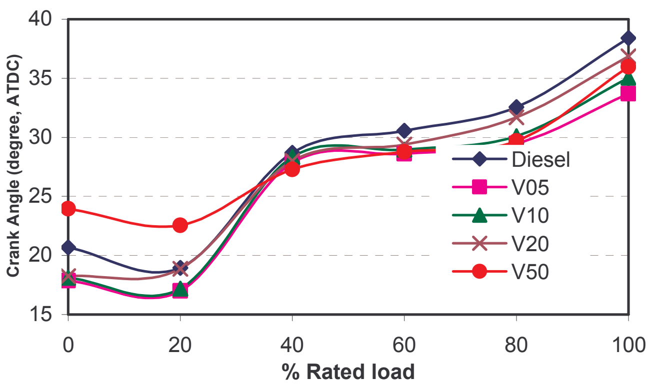

Figure 10: Crank angle degree for 90% fuel mass burning at 2000 rpm

Vegetable oil blends have lower volatility and higher flash point in comparison to mineral diesel, which might cause slower burning of vegetable oil blends and work against the lower ignition delay observed for vegetable oil blends. Higher volume of fuel is injected in case of vegetable oil blends because of their lower calorific value of these blends in comparison to mineral diesel.

Combustion duration is regarded as the crank angle interval between 5% and 90% fuel mass burn. Figure 11 show the combustion duration for vegetable oil blends compared with base line data of mineral diesel.

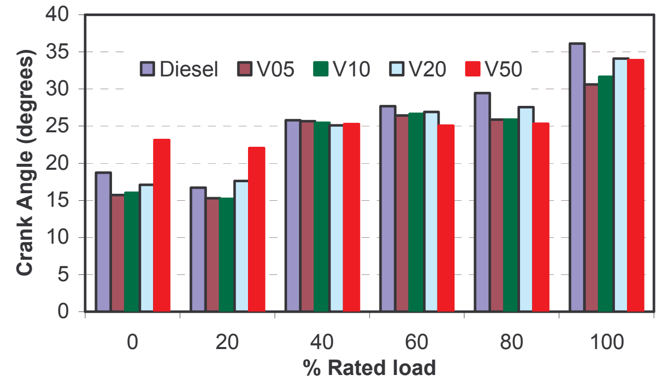

Figure 11: Variation in combustion duration at 2000 rpm

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 comes closer to mineral diesel.

CONCLUSIONS

Analysis of pressure-crank angle history and heat release analysis indicates that all fuel blends exhibits almost similar combustion stages as mineral diesel and no undesirable combustion features such as knocking were observed. 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 almost similar for vegetable oil blends compared to mineral diesel. However cylinder pressure rise for all vegetable oil blends was found to be higher than mineral diesel and a stable and smoother engine operation was observed with all fuels. Hence it can be concluded that vegetable oil blends can be used in the engine without any hardware modification in the engine without any undesirable combustion features. It can be seen that vegetable oil blends show combustion characteristics almost identical to diesel. Therefore blending of vegetable oil can be used in compression ignition engines used for transportation, however long – term endurance and durability need to be performed.

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