Rice bran oil methyl ester fuelled medium-duty transportation engine: long-term durability and combustion investigations

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Rice bran oil methyl ester fuelled medium-duty transportation engine: long-term durability and combustion investigations

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Abstract: Increased environmental awareness and depletion of resources are driving industry to develop alternative fuels that are environmentally more acceptable. In present investigation, biodiesel from rice bran oil is developed and characterised as per ASTM D6751 and found to be comparable with mineral diesel. Steady state engine dynamometer tests have been carried out to evaluate the performance and emission characteristics (ECE R49 test cycle) of a medium duty transportation direct injection diesel engine fuelled with various biodiesel blends ranging from B00 to B100. Combustion characteristics of the same engine running with diesel, biodiesel and B20 (20% biodiesel) blend have been investigated. In addition, endurance tests were conducted under predetermined loading cycles in two phases: engine operating on mineral diesel and engine fuelled with B20 blend. To quantify the wear of cylinder liner, surface parameters and scanning electron microscopy (SEM) at different location in the liner were done. Wear metal analysis and ferrography of lubricating oil samples drawn from both phase of engine operation were also carried out.

Keywords: biodiesel; combustion; endurance; engine wear; heat release analysis.

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1 Introduction

The world is confronted with the twin crises of fossil fuel depletion and environmental degradation. Petroleum resources of most of the non-OPEC countries have already peaked or are going to peak in the near future (Agarwal, 2007). On the other hand, there is universal acceptance of the need to reduce vehicular emissions. Over the past few decades, diesel engine technology has improved significantly. As a result, diesel cars are faster, more efficient, drive better and are quieter than ever before, and these engines are gaining popularity in the passenger car segment also. Compared to the rest of the world, India's demand for diesel fuel is roughly five times that of gasoline (39% of the total petroleum products) (Subramanian et al., 2005). Recent events around the world have once again put energy security, and in particular oil import dependence, at the top of energy agenda of several countries of the world. Increasing dependence on oil import has become a serious cause of concern for India. In 2005–2006, consumption of petroleum crude has increased to approximately 130 MMT (million metric tones), more than 75% of it was imported. The import bill has increased substantially during the last two decades (US$ 1.36 billion in 1991 to a whopping US$ 38.1 billion in 2005–2006), which constituted 37% of the net export earnings (Anon, report of Ministry of oil and natural gas, Government of India). Therefore, the issue of biofuels, especially in diesel engines, is very important for India.

Many countries have a general interest in vegetable oil as an alternative fuel to mineral diesel. However, the use of unmodified vegetable oils results in problems such as severe engine deposits, injector coking and piston ring sticking (Peterson, Wagner and Auld, 1983; Clark et al., 1984; Murayama et al., 1984; Rewolinski and Shaffer, 1985; Peterson and Auld, 1991; Srivastava and Prasad, 2000; Kowalewicz and Wojtyniak, 2005). Hence, vegetable oils need to be modified to bring their properties closer to mineral diesel. Among the various fuel modification techniques, transesterification is the most effective and widely used technique for formulating properties of vegetable oils (Freedman, Pryde and Mounts, 1984; Srivastava and Prasad, 2000; Fukuda, Kondo and Noda, 2001; Vicente, Martinez and Aracil, 2004; Gerpan, 2005; Marchetti, 2007). Biodiesel (monoalkyl esters) is a biodegradable, non-toxic, essentially sulphur free, renewable fuel and can be produced from agriculture and plant resources available locally. Biodiesel degrades four times faster than mineral diesel and carbon cycle time for fixation of CO_2 from biodiesel is quite small compared with that for mineral diesel (Peterson and Hustruid, 1998). Several experimental investigations have been carried out by researchers around the world to evaluate the engine performance of different biodiesel blends. Generally a slight amount of power loss, reduction in torque and increased brake specific fuel consumption (BSFC) was observed in case of biodiesel-fuelled engines (Kaufman and Ziejewski, 1984; Altin, Cetinkaya and Yucesu, 1991; Mcdonald et al., 1995; Agarwal and Das, 2001; Raheman and Phadatare, 2004; Sinha and Agarwal, 2005). Fuel injection and heat release are reported to take place earlier in case of biodiesel as compared to mineral diesel (Laforgia and Ardito, 1995; Zhang and Gerpan, 1996; Senatore et al., 2000; Rakopoulos, Antonopoulos and Rakopoulos, 2007; Tsolakis et al., 2007; Sinha and Agarwal, 2007a; Lapuerta, Armas and Rodrıguez-Fernandez, 2008). The effect of fuel on engine performance and wear of engine components are very important as it affects the fuel economy, emissions as well as engine durability. The main causes of wear are metal-to-metal contact, presence of abrasive particles and attack by corrosive acids. Development of more fuel efficient and compact automobile engines lead to decreasing oil film thicknesses between the interacting surfaces of these components and a more crucial role for the topography and surface profile of the two surfaces. Several researchers reported that soot is one of the main factors which increases engine wear as it interacts with oil additives and reduces the effectiveness of anti-wear additives, (Nagai et al., 1983; Gautam et al., 1999).

Cylinder liner wear mainly corresponds to wear of the surface topography in the peak and core zones. The valley zone is less affected. Boundary lubrication occurs at top dead center (TDC) and bottom dead center (BDC) positions and hence, surface wear at TDC and BDC locations is more severe than at the middle (Dong et al., 1995; Taylor and Priest, 2000). Wear particles are washed away with lubricating oil so metallic wear debris present in the lubricating oil provide a detailed information about the condition of the engine. Atomic absorption spectroscopy (AAS) is one of the most commonly used techniques for qualitative and quantitative analysis of wear debris in lubricating oil (Palus, 1998; Agarwal, Bijwe and Das, 2003a; Agarwal, Bijwe and Das, 2003b; Sinha and Agarwal, 2007b). Kaufman and Ziejewski (1984) conducted 200-hour engine manufacturers association (EMA) durability test with sunflower methyl ester as a fuel on turbocharged, intercooled direct injection and found physical measurements on engine did not indicate any significant wear. Less carbon build up in the intake ports, intake valve tulips, comparable carbon build up in the exhaust port and slightly more carbon deposits were observed on the valve stems, cylinder sleeves above the ring travel area and piston top land with biodiesel as fuel.

Clark et al. (1984) reported comparable deposits on engine parts, but slightly different in colour and texture, with the methyl ester engine experiencing greater carbon and varnish deposits on the piston. In all cases, the original honing marks in the liners were clearly visible. Slightly higher levels of aluminium and lead in lubricating oil were reported with methyl ester. Agarwal, Bijwe, and Das (2003a) and Agarwal, Bijwe, and Das (2003b) performed long-term endurance test on a constant speed diesel engines with 20% linseed oil biodiesel blend and found less carbon deposits and lower wear (≈30% lower) of engine parts in case of 20% linseed oil methyl ester fuelled engine. A lot of literature is available on the performance and emission characteristics of biodiesel-fuelled engines but in depth combustion analysis for transportation engine and engine wear and lubricating oil tribology investigations are seldom available. In the present study different blends of rice bran oil methyl ester and mineral were selected for performance and emission investigation and 20% blend was selected for wear and lubricating oil tribology investigations.

2 Biodiesel production and characterisation

Rice bran oil was transesterified, using methanol in presence of NaOH catalyst. Process parameters for such as temperature, catalyst amount, molar ratio of alcohol to oil and reaction temperature were optimised and it is found that 9 : 1 molar ratio of alcohol to oil, 55°C temperature, 0.75% (ww^{-1}) catalyst and one-hour reaction time is optimum for transesterification of rice bran oil. For transesterification, rice bran oil was heated in a round bottom flask and NaOH was dissolved in methanol in a separate vessel and was poured into round bottom flask, while stirring the mixture continuously. The mixture was stirred while being maintained at 55°C for one hour. The reaction products were kept in a separating funnel for 24 hours. The products formed during transesterification were rice bran oil methyl ester and glycerol. The glycerol (high density) is separated out through gravity separation. The ester was washed with (10% vv^{-1}) warm water (70°C) and kept for 24 hours for removal of catalyst. The catalyst gets dissolved in water, which is then gravity separated. This biodiesel is then blended in required quantities to form appropriate blends. The blends were referred as B*xx* where *xx* refers the percentage of ester in that blend. Characterisation of rice bran oil, rice bran oil methyl ester (ROME) and diesel were done in laboratory as per american society of testing and materials (ASTM) standards. Some fuel properties evaluated are shown in the Table 1, while Table 2 shows typical values of fatty acid composition for rice bran oil taken from the literature (Srivastava and Prasad, 2000; Zullaikah et al., 2005).

Table 1 Properties of fuels

Property		*Test method*	*Diesel*	*ROME*
Specific gravity @ 30°C		–	0.839	0.877
Viscosity (cSt) @ 40°C		ASTM D445	3.18	5.29
Cetane No.		ASTM D613	51	63.8
Cloud/Pour point (°C)		ASTM D2500	6/–7	9/–2
Flash/Fire point (°C)		ASTM D93	68/103	183/196
Net Calorific Value ($MJkg^{-1}$)		ASTM D240	44.8	42.2
Elemental Analysis (%ww^{-1})	C	–	83	72.96
	H	–	13	12.73
	N	–	1.76	0.94
	O	–	0.19	11.59
	S	–	0.05	ND

Table 2 Fatty acid composition of rice bran oil

Fatty acid	*Molecular Weight*	*Srivastava and Prasad (2000)*	*Zullaikah et al. (2005)*
Myristic (14 : 0)	228	0.4–0.6	0.21±0.1
Palmitic (16 : 0)	256	11.7–16.5	14.7±0.47
Stearic (18 : 0)	284	1.7–2.5	1.86±0.22
Oleic (18 : 1)	282	39.2–43.7	42.2±0.68
Linoleic (18 : 2)	280	26.4–35.1	37.8±0.51
Linolenic (18 : 3)	278	–	2.39±0.1
Arachidic (20 : 0)	312	0.4–0.6	n.d.
Behenic (22 : 0)	340	–	0.2±0.1
Lignoceric (24 : 0)	368	0.4–0.9	0.3±0.14

Keeping in view to utilise biodiesel in transportation sector specially cars and medium duty vehicles, a typical medium duty transportation compression ignition direct injection (CIDI) engine (Make: Mahindra and Mahindra Ltd, India, Model: MDI-3000) was used for conducting engine investigations. The specifications of the engine are given in Table 3. The inlet valve opens 5° before top dead center (BTDC) and closes 35° after bottom dead center (ABDC). The exhaust valve opens 42° before bottom dead center (BBDC) and closes 10° after top dead center (ATDC). Tappet clearance recommended by manufacturer at cold condition for inlet valves are 0.016/0.014 inch and for exhaust valves are 0.020/0.018 inch.

Table 3 Specification of the test engine

Manufacturer/Model	*Mahindra and Mahindra Ltd, India/ MDI 3000*
Type of engine	Four stroke, Naturally aspirated, Water cooled diesel engine
Number of cylinders	Four
Combustion System	Direct injection, Re-entrant bowl
Bore/stroke	88.9/101.6 mm
Displacement volume	2520 cc
Direction of rotation	Anti-clockwise (flywheel side)
Compression ratio	18 : 1
Fuel injection pump	In-line, reciprocating
Fuel injection timing/opening pressure	15±1°BTDC/214 bar
Rated power	55 hp at 3000 rpm
Max. torque	152 Nm at 1800 rpm

The engine was coupled with an eddy current dynamometer and controller (Make: Schenck Avery, India; Model: ASE 70). Suitable instrumentation was done for conducting various experiments. Engine speed and load was controlled by varying excitation current to the eddy current dynamometer. Schematic diagram of experimental setup is shown in Figure 1. A piezoelectric pressure transducer (Make: AVL, Austria; Model: GU21C) was installed in the engine cylinder head for the first cylinder in order to measure the combustion pressure. Signals from the pressure transducer were amplified using a charge amplifier. A high precision magnetic shaft encoder was used for delivering signals for TDC and crank angle with a precision of 0.1 crank angle degrees (CAD). The signals from the charge amplifier and shaft encoder were acquired using a high-speed data acquisition system (Make: AVL, Austria; Model: Indimeter-619).

The exhaust gas emissions such as CO, HC, NO_x, CO_2 and O_2 were measured by raw exhaust gas emission analyser (Make: Horiba, Japan; Model: EXSA-1500). The exhaust gas analyser consists of non-dispersive (NDIR) CO/CO_2 analyser, flame ionisation detector (FID) THC analyser and chemiluminiscent NO_x analyser. The sampling line is kept at a constant temperature of 181°C. Observed value for each emission species converted into specific mass emissions (on wet basis) and NO_x concentration were also corrected for humidity as per SAE procedure SAE J1003 and Indian standard IS: 14273.

Performance and emissions tests were conducted to find the suitability of different biodiesel blends ranging from B00 (mineral diesel) to B100 (100% biodiesel) through 5, 10, 20, 30 and 50%. Further, emissions were measured and determined for 13-mode emission test (ECE R49 and IS: 14273, 1999). The engine operating conditions and weighing factor for each mode is shown in Figure 2.

Figure 1 Schematic diagram of experimental setup (see online version for colours)

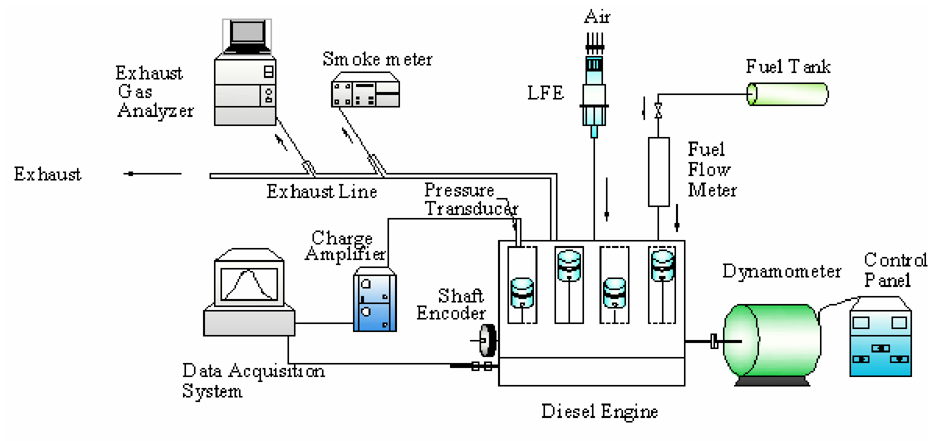
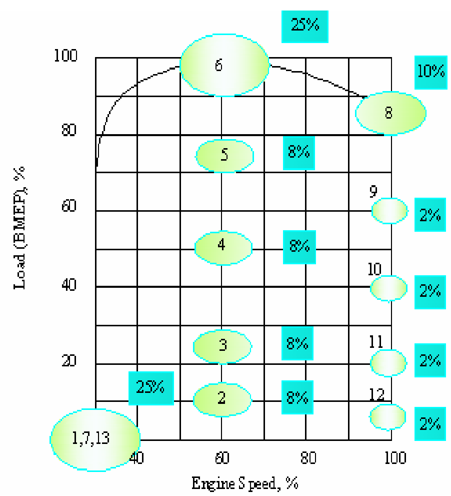


Figure 2 13-mode emission test cycle (ECE R49) (see online version for colours)



The experimental work started with a preliminary investigation of the engine running on neat diesel fuel, to get the base line data. The same procedure was repeated for each fuel blend by keeping the same operating conditions. For every fuel change, engine was left to operate for about 15 min to stabilise at its new condition. The differences in the measured performance and exhaust emission parameters from the 'baseline' operation of the engine and between biodiesel blends were determined and compared.

After conducting performance, emission and combustion characteristics investigations 20% blend of rice bran biodiesel (B20) was found to be optimum blend and selected for long-term endurance test. The long-term (engine run) endurance experiment was conducted in two phases. In the first phase, the engine was run with diesel (B00) and in the second phase, the engine was run with B20 blend. Engine was dismantled and new set of cylinder liners, pistons, piston rings, big end bearings were used for conducting experiment for each of the two phases. The endurance test was performed as per Indian standard IS: 10000 (1980). The test was conducted for a total of 100 hours duration and consisted of 10 non-stop running cycles of 10 hours duration, each. Each running cycle consists of five repetitive runs of two-hour duration each (Table 4). The lubricating oil samples were collected from the engine after every 20 hours for wear metal analysis.

Lubricating oil samples were analysed on a flame atomic absorption spectroscope (AAS) for evaluating the metallic composition of wear debris. The cylinder liner surface profile was evaluated for various surface characteristics before and after completion of each phase. The surface profiles of the cylinder liner surfaces were taken using stylus based surface profilometer (Make: Mitutoyo, Japan; Model: SJ-301). Surface roughness is determined from the vertical stylus displacement produced during the stylus traverse over the surface irregularities.

Table 4 Engine loading for endurance test

Engine speed	*Load (% rated load)*	*Running time (min)*
Max speed	75	50
Max torque speed	100	45
Idling	No load	5
Max speed	100	20

3 Results and discussions

3.1 Performance and emission tests

A series of exhaustive engine tests were carried out using mineral diesel and different biodiesel blends ranging (B05–B100) at 1800 rpm and at loads of 25, 50, 75 and 100% of the full load. In each test, maximum engine torque, volumetric fuel consumption and exhaust smoke opacity are measured. The engine performance and emissions data obtained for biodiesel blends were compared with the baseline data of mineral diesel. Exhaust gas regulated emissions such as nitrogen oxides (NO_x), carbon monoxide (CO) and total unburned hydrocarbons (HC) are measured for prescribed 13-mode (Figure 2) cycle.

Characteristic curves for brake power, torque, BSFC and brake thermal efficiency, were drawn for different biodiesel blends and mineral diesel. These characteristic curves are shown in Figures 3–5. The variation of maximum torque produced by the engine at 1800 rpm using different fuel blends is shown in Figure 3. Torque is found to be slightly lower (1–1.5%) for biodiesel blends compared to mineral diesel. Figure 4 shows the variation of brake power for different fuel blends. At full load slightly less power was observed with biodiesel blends may be due to lower calorific value of biodiesel (ROME), part load results are just the direct consequence of full load result. The characteristic curves for BSFC and thermal efficiency of the engine for different fuel blends are shown in Figures 5–6. Figure 5, reflects that BSFC is lower for B05, B10 and B20 compared to mineral diesel, the BSFC increased with further increase in biodiesel in the blends. The increased fuel consumption (BSFC) with the increase of the biodiesel content in the fuel blend is mainly due to the lower calorific value of ROME compared to those for the mineral diesel fuel. However, BSFC is not a rationale parameter for comparing the fuels having different calorific values. Brake thermal efficiency is the inverse of the product of the BSFC and the lower calorific value. Hence, it actually represents the energy consumption. The fuel blend calorific value is calculated from the respective values of the fuels involved, by taking into account their blending ratio. Therefore, engine characteristic curves for thermal efficiency are also drawn (Figure 6). It shows that thermal efficiency curves for all the blends except 100% biodiesel (B100) was not affected significantly and closely follow mineral diesel curves. The B20 shows maximum improvement in thermal efficiency (Figure 6). In case of B20, 0.3–2% improvement in the efficiency was observed. For 100% biodiesel, 2–3% drop in thermal efficiency is observed. This reduction is attributed to comparatively higher viscosity of B100, which affects the spray characteristics of fuel in combustion chamber. Therefore, the selection of biodiesel content in the blend is very important for optimum engine performance and fuel economy.

Figure 3 Maximum torque produced by engine for different fuel blends at 1800 rpm (see online version for colours)

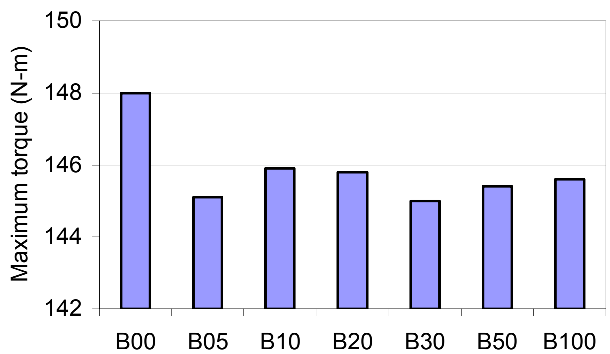


Figure 4 Power produced by engine for different fuel blends (see online version for colours)

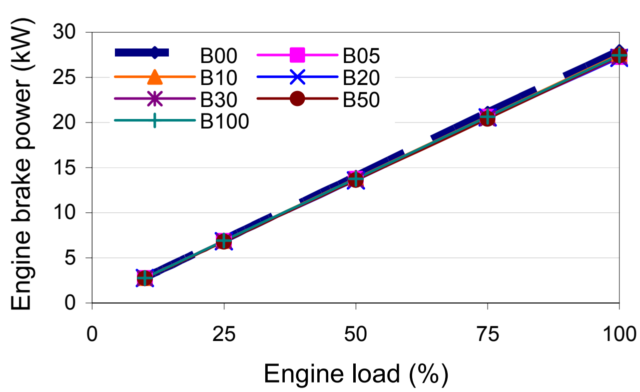


Figure 5 Brake specific fuel consumption for different fuel blends (see online version for colours)

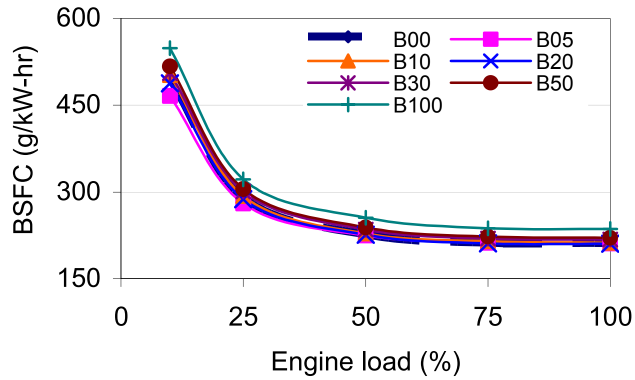
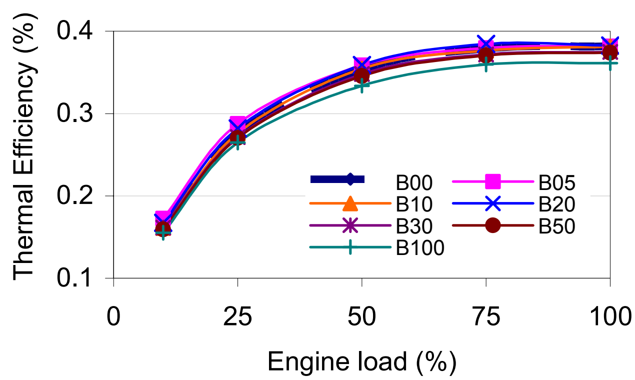


Figure 6 Thermal efficiency for different fuel blends (see online version for colours)



Exhaust gas smoke opacity for different fuels is shown in Figure 7. Exhaust gas opacity increases with engine load but found to have decreased as the proportion of biodiesel in the blend increases. This may be due to the fact that oxygen content of the biodiesel molecule enables more complete combustion even in regions of the combustion chamber with fuel-rich diffusion flames and promotes the oxidation of the already formed soot. The amount of soot precursor species available to produce soot strongly depends on the amount of oxygen available in the mixture. When sufficient oxygen is available, soot precursor species react with molecular oxygen or oxygen-containing radicals (such as OH, O) and eventually produce CO rather than aromatics and soot. Reduction in smoke opacity is also due to the lower sulphur content of the biodiesel which leads to less particulate matter emissions (Tsolakis et al., 2007; Lapuerta, Armas, and Rodrıguez-Fernandez, 2008; Rakopoulos et al., 2008). Rakopoulos, Antonopoulos and Rakopoulos (2007) developed multizone combustion model and reported low fuel-to-air equivalence ratio area within the fuel spray with biodiesel fuel instead of mineral diesel.

For measurement of exhaust emissions, engine was operated using different fuel blends on the prescribed sequence of loading conditions (Figure 2) and results are shown in Figures 8–10. CO emissions (Figure 8) are found to be relatively lower for biodiesel blends as fuel compared to mineral diesel. Further, CO emissions reduce as the concentration of biodiesel in the blend increases. As compared to mineral diesel, CO emissions are found to decrease by 21.4 % for B20 and 40.7% for B100. This reduction in CO emissions is due to oxygen content in the biodiesel which enhances the complete combustion. Lapuerta, Armas, and Rodrıguez-Fernandez (2008) concluded in their review work that increased cetane number and advance injection may also reduce the CO emissions.

Figure 7 Smoke opacity for different fuel blends (see online version for colours)

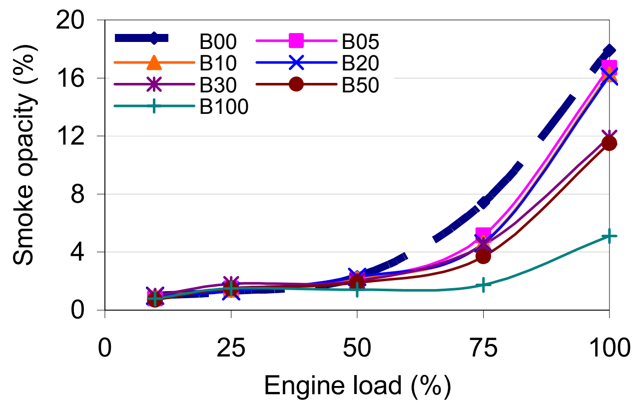


Figure 8 CO emissions for different fuel blends (see online version for colours)

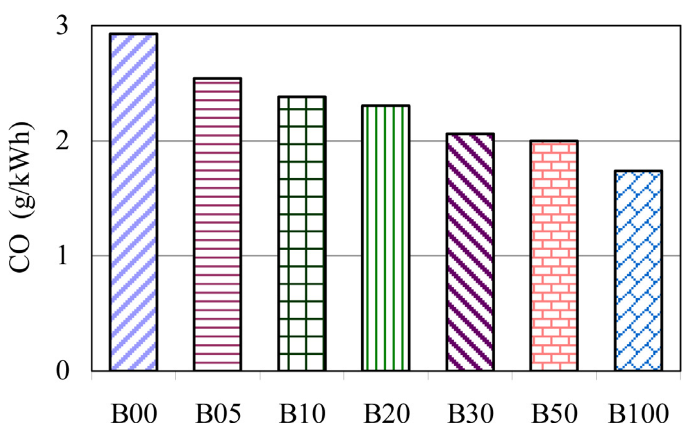


Figure 9 HC emissions for different fuel blends (see online version for colours)

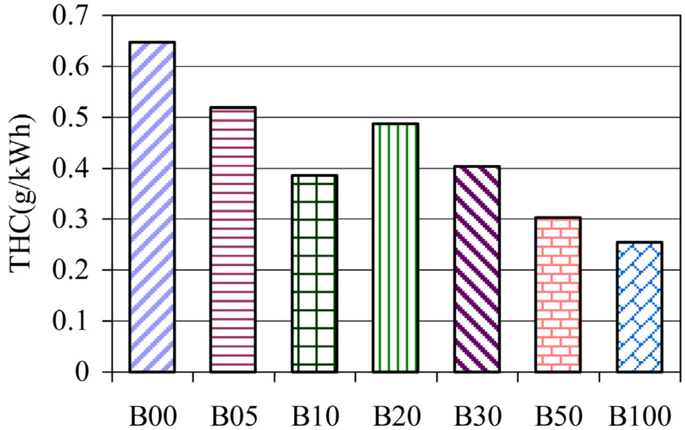
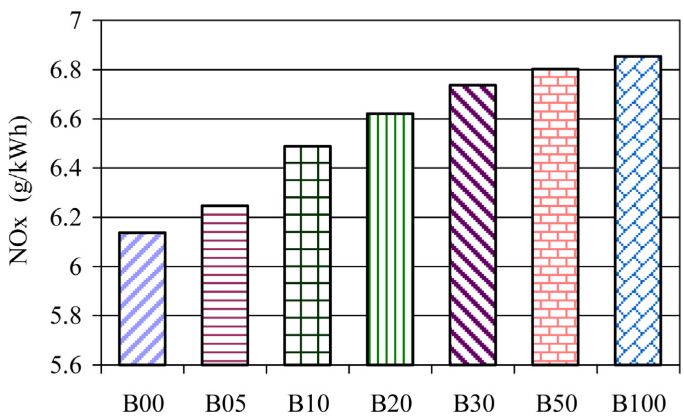


Figure 10 NO_x emissions for different fuel blends (see online version for colours)



HC emissions (Figure 9) are also found lower for biodiesel blends compared to baseline mineral diesel and HC emissions reduce as the concentration of biodiesel in blend increases. The longer carbon chains and absence of aromatic compounds leads to higher cetane rating of biodiesel (ROME) compared to mineral diesel thus promoting complete combustion and reducing the level of hydrocarbon emissions. As compared to base line data for mineral diesel HC emissions are found to be lower by 24.7% for B20 blend and 60.5% for B100. Further, higher oxygen content in the biodiesel molecule and higher cetane number (lower ignition delay) of biodiesel may be related to decrease in HC emissions (Lapuerta, Armas and Rodrıguez-Fernandez, 2008).

Brake specific NO_x emissions (Figure 10) are found to be higher for biodiesel blends compared to baseline mineral diesel. Further, NO_x emissions increase with concentration of biodiesel in blend. NO_x is found to be increase by 7.9% for B20 blend and 11.7% for B100. Although the little higher cetane number (shorter ignition delay and so lower temperatures during the premixed combustion part) and the absence of aromatics tend to contribute to less NO_x production, these factors do not seem to offset the increase caused by the presence of the fuel-bound oxygen even in locally rich zones. The increase of NO_x emissions in the engine exhaust may be associated with the oxygen content of the biodiesel blends, since the fuel oxygen provides additional oxygen for NO_x formation. At the same time, impact of the fuel's physical properties on the engine's injection also plays an important role in NO_x formation and emissions from biodiesel-fuelled engines. Most researchers propose that the combustion process is advanced as a consequence of the advanced injection derived from the physical properties of biodiesel (viscosity, density, compressibility and sound velocity). When biodiesel is injected, the pressure rise produced by the pump is quicker as a consequence of its lower compressibility (higher bulk modulus) and also propagates more quickly towards the injectors as a consequence of its higher sound velocity. In addition, the higher viscosity reduces leakages in the pump leading to an increase in the injection line pressure. Therefore, a quicker and earlier needle opening is observed with respect to the case of diesel fuel (Rakopoulos, Antonopoulos and Rakopoulos 2007; Lapuerta, Armas and Rodrıguez-Fernandez, 2008). Advance in injection timing was also found during combustion investigations and it is also one of the reasons for increase in the NO_x emissions from the engine.

3.2 Combustion investigations

Fuel samples including mineral diesel (B00), B20 and biodiesel (B100) were tested at five different engine loads (no load, 25, 50, 75 and 100% of rated load) at engine speed of 1800 rpm. The variation of cylinder pressure with crank angle, heat release rate diagrams, peak cylinder pressure and crank angle at which peak pressure are shown in Figures 11–14. In a compression ignition engine, cylinder pressure characterises the ability of the fuel to mix well with air and burn. The variation of cylinder pressure with crank angle for all the blends at different engine operating conditions is shown in Figures 11–12.

Figure 11 Pressure crank angle diagram at no engine load at 1800 rpm (see online version for colours)

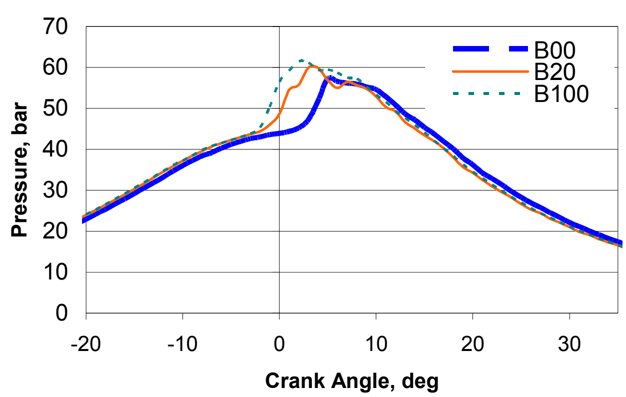


Figure 12 Pressure crank angle diagram at rated engine load at 1800 rpm (see online version for colours)

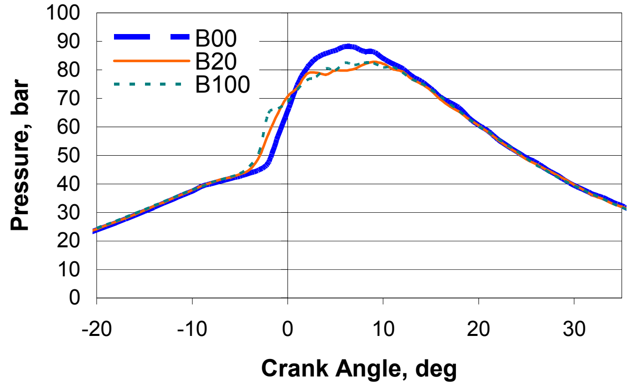


Figure 13 Instantaneous rate of heat release at rated engine load (see online version for colours)

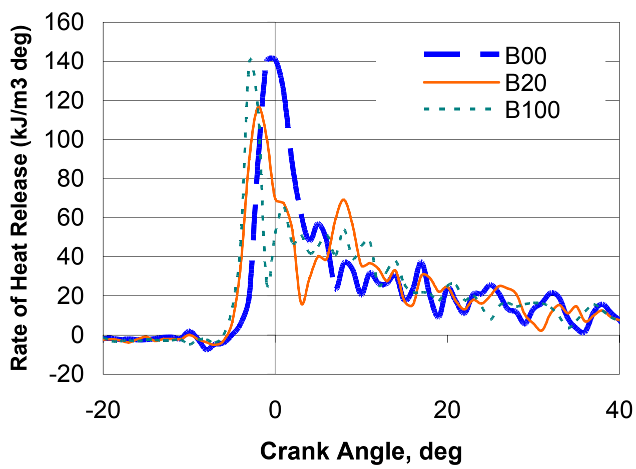
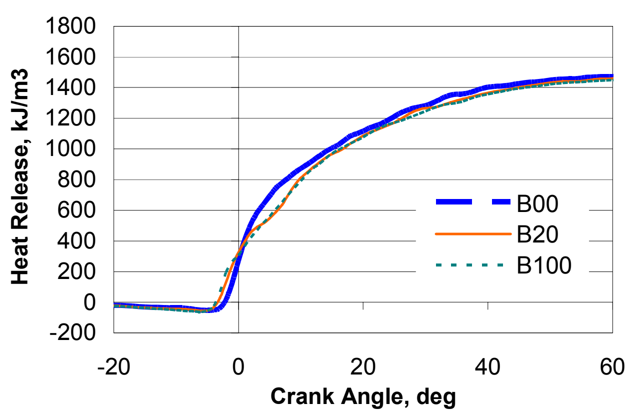


Figure 14 Cumulative heat release at rated engine load (see online version for colours)



From Figures 11–12, it is clear that peak pressure increases as the engine load increases. Peak pressure is higher for biodiesel blends at no load (Figure 11) but at higher engine load, peak pressure for diesel is higher (Figure 12). Peak pressure for diesel is higher due to longer ignition delay, during which more fuel gets accumulated in the combustion chamber to release higher heat during premixed combustion phase. The possible reason for the opposite trends in peak pressure at low and high engine loads is because ignition delay increases with decrease in engine load. At very low engine loads due to higher ignition delay, combustion starts later for diesel compared to biodiesel blends. As a result, peak cylinder pressure attains a lower value being further away from TDC in the expansion stroke at low engine loads. Combustion starts earlier for biodiesel blends compared to diesel. As the engine load is increased, combustion start point comes closer for all the fuels. Combustion starts earlier for biodiesel partially due to shorter ignition delay (higher cetane no.) and partially due to advanced injection timing (due to higher bulk modulus and higher density of biodiesel) (Sinha and Agarwal, 2007a). Figures 13–14 show the heat release rate diagrams for these fuels. Due to vaporisation of the fuel accumulated during ignition delay, negative heat release in the beginning is observed and this becomes positive after combustion is initiated. All biodiesel blends experience identical combustion stages as diesel. It can be observed that combustion starts earlier for biodiesel blends under all engine operating conditions as found by other researchers (Laforgia and Ardito, 1995; Zhang and Van Gerpan, 1996; Senatore et al., 2000), and it becomes more prominent with higher biodiesel blends. The premixed combustion heat release is higher for diesel due to higher volatility and better mixing of diesel with air. Another reason possibly may be longer ignition delay of diesel leading to higher amount of fuel accumulation in combustion chamber at the time of pre-mixed combustion stage, leading to higher rate of heat release. Combustion for diesel starts later but quickly it exceeds the cumulative heat released for biodiesel blends, suggesting faster burn rate of diesel. Cumulative heat release decreases as the proportion of biodiesel increases in the blend, due to the lower heating value of the biodiesel.

3.3 Long-term endurance test

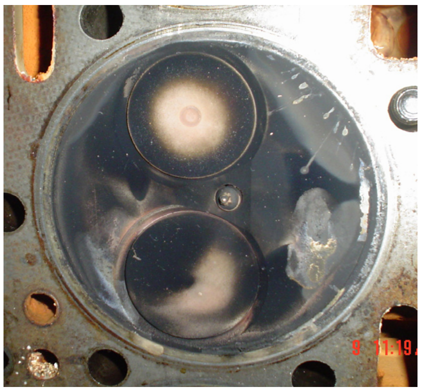
Further, 100-hours endurance test on the same engine using B20 and mineral diesel as fuels, respectively, in two phases were conducted as per Indian standards IS: 10000. The engines were dismantled at the end of the tests and it was found that engine operating on both the fuels operated successfully without any major repairs during the test durations. Important observation was that in case of B20, lower wear of the engine components along with lower carbon deposits on the piston, cylinder head and injector tip were observed.

3.4 Carbon deposits on vital parts

The physical conditions of various vital engine components directly exposed to combustion (after endurance test) are shown in Figure 15. It can be clearly seen from the photographs that carbon deposits on cylinder head, Injector tips and piston top of biodiesel-fuelled engine is significantly lower than that of mineral-diesel fuelled engine. This shows that main hurdle in utilising straight vegetable oils/blends, i.e. large carbon deposits and coking of injector tip disappeared after the transesterification of vegetable oils. This may be due to improved combustion and lower soot formation in case of biodiesel due to presence of oxygen in its molecule.

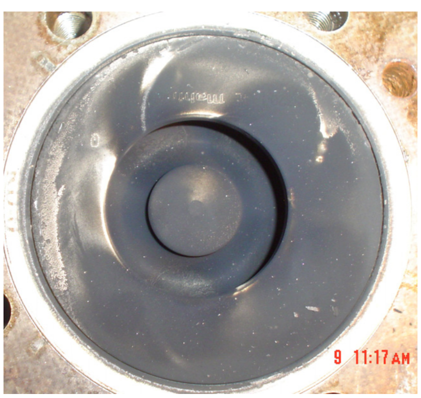
Figure 15 Carbon deposit on various in-cylinder engine parts (see online version for colours)

Mineral Diesel fuelled engine



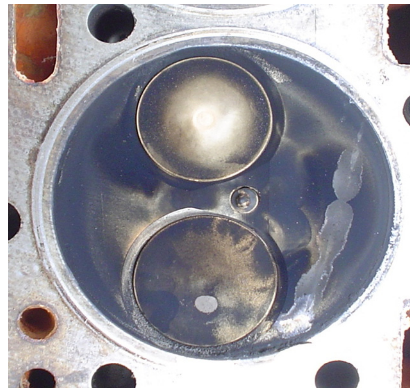
Cylinder Head

Injector Tip



Piston Crown

Biodiesel (B20) fuelled engine

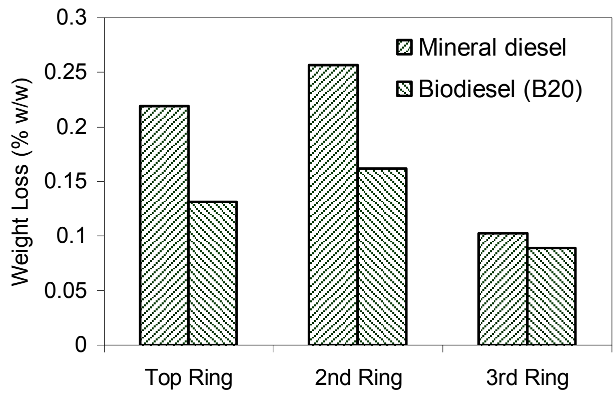


Cylinder Head

Injector Tip

Piston Crown

Figure 16 Percent weight loss of piston rings after 100 hours of engine operation



3.5 Piston rings wear

The percentage weight loss of rings for both phase of experiments are shown in Figure 16. It was observed that second compression ring had maximum weight loss and oil control ring had the minimum weight loss for engine operating on mineral diesel as well as biodiesel. In case of engine fuelled with biodiesel, lower weight loss (≈38%) for compression rings as well as for oil control ring (≈14%) was observed. Possible reasons may be the improved biodiesel combustion, lower peak in-cylinder temperature, less soot formation and better lubricity property of the biodiesel.

3.6 Wear metal analysis of lubricating oil

Wear debris originates from various sliding and rotating components in engine and are washed away by lubricants and finally get accumulated in the oil sump. Various metals such as Fe, Cu, Cr, Al, Zn, Mg and Pb in the lubricating oil samples drawn at the regular intervals from both phases of engine experiments were analysed by AAS. Each of these metals can be traced back to several engine parts and the results are shown in Figures 17–18. Increasing trend (initial faster rise followed by slow and steady rise) of metallic concentration in the lubricating oil with usage for both experimental phases were observed. This may be due to initial running-in of engine parts. Concentration of metals was found (except Pb and Al) to be lower in case of used lubricating oil of biodiesel-fuelled engine showing lower wear. In addition, Clark et al. (1984) and Staat and Paul (1995) reported more lead present in the used lubricating oil of biodiesel-fuelled engine. Lower concentration of Cr in used lubricating oil of biodiesel-fuelled engine again shows the lower wear of piston rings in case of biodiesel-fuelled engine.

In the present investigation, it has been found that concentration of zinc (Figure 18) in the lubricating oil gets reduced during initial hours of engine operation but after 20 hours the concentration rises for both phases of experiments.

The reduction in zinc concentration for the initial period may be because of evaporation of zinc containing species from the lubricating oil due to initial thermal stressing of lubricant. After that, zinc gets added to lubricating oil due to wear of various engine parts, thus increasing the concentration of zinc in lubricating oil continuously (Sinha and Agarwal, 2007b).

Figure 17 Metal concentration in lubricating oil after 100 hours endurance test (see online version for colours)

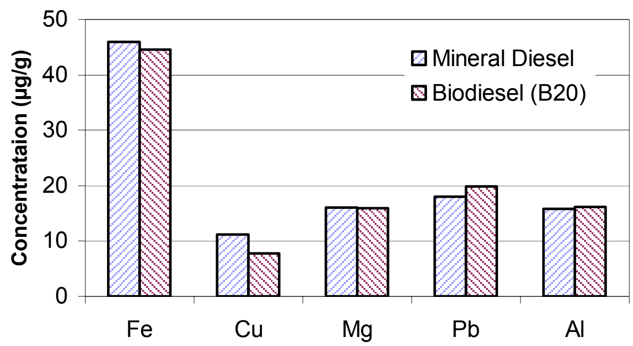


Figure 18 Variation of chromium and zinc concentration in lubricating oil (see online version for colours)

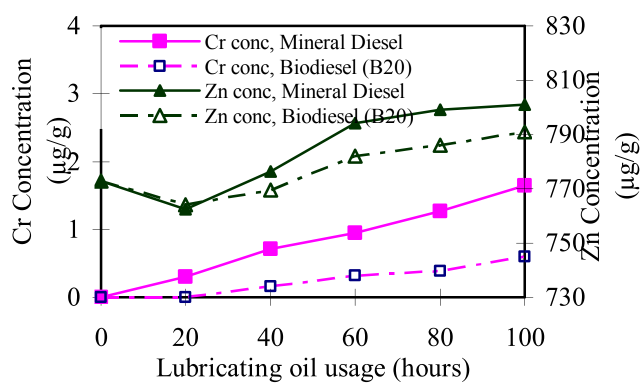
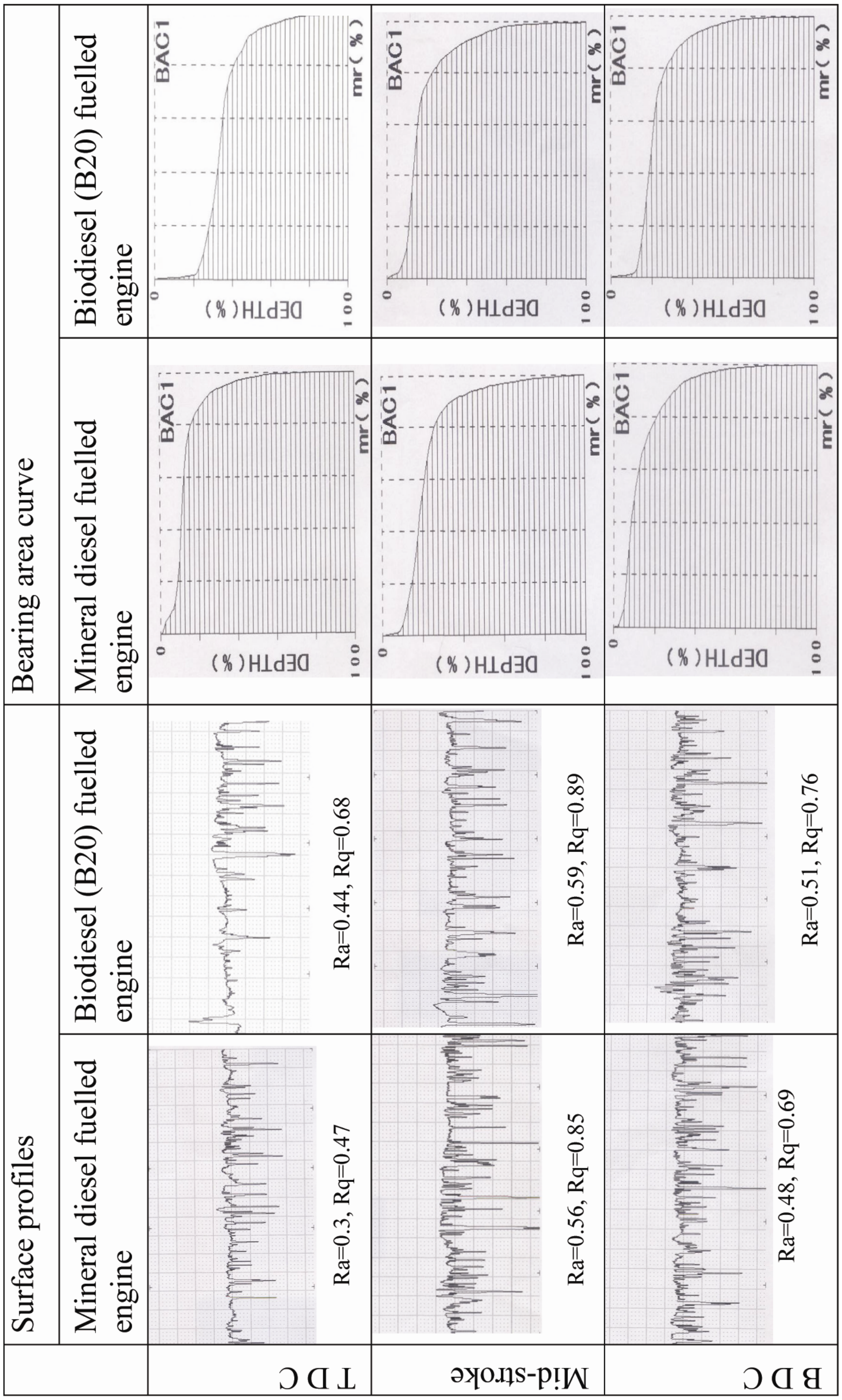


Figure 19 Surface profiles and bearing area curves of liner surface of mineral diesel and biodiesel fuelled engine after endurance test



3.7 Cylinder liner wear

For assessing the wear of the liner and to make qualitative comparison between the wear of liner surface profiles of the liners were evaluated at three locations, i.e. TDC, mid-stroke and BDC. Profiles were taken before and after the endurance test nearly on the same locations for both sets of experiments. The roughness profile along with average roughness (R_a) and root mean square roughness (R_q) value for liner after endurance test and bearing area curve (BAC) at theses locations are shown in Figure 19. The surface profilometer evaluates the surface texture and gives a number of surface parameters such as R_a, R_q, R_p, $R_{v,}$ etc. The evaluation length of the surface profile was kept 4.0 mm. The profiles were taken with 20 times magnification (0.5 mm cm^{-1}) in horizontal direction and 5000 times magnification (2.0 μm cm^{-1}) in vertical direction. From these roughness parameters, it can be observed that the wear of the liner at TDC is higher than BDC and mid stroke positions. The wear found at TDC location is higher because at dead centre positions, boundary lubrication takes place while at mid stroke location hydrodynamic lubrication takes place. In addition, the TDC zone faces highest temperature and pressure due to combustion taking place near TDC. Due to these extreme conditions, breakdown of the oil film takes place, leading to relatively higher wear at this location.

The wear of cylinder liner surfaces after 100-hours endurance test was compared qualitatively by SEM as shown in Figure 20. It has been observed that honing depth is not removed; honing marks become less pronounced as compared to fresh liner for both set of experiments. Smoother surface (less pronounced crosshatched marks) indicates higher extent of wear. Overall, wear of cylinder liner for B20 is lower in comparison to mineral-diesel fuelled engine. Similar results were found during wear metal analysis and surface profilometry.

Figure 20 Scanning electron micrographs of cylinder liner surface

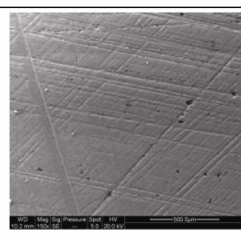
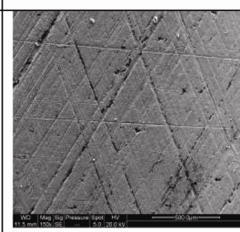
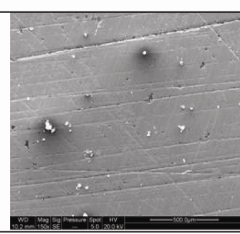
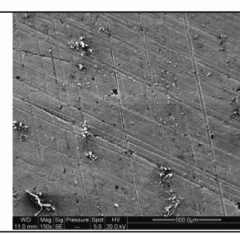
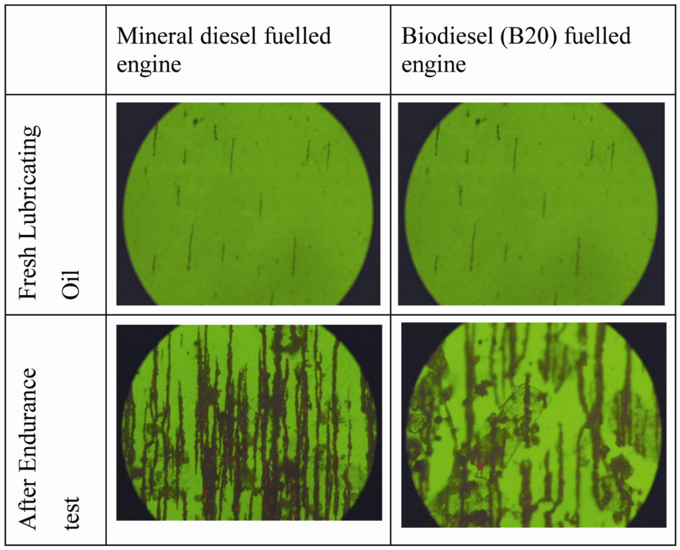
	SEM of cylinder liner	
	Mineral diesel fuelled engine	Biodiesel (B20) fuelled engine
Before Endurance test		
After Endurance test		

Figure 21 Ferrograms of lubricating oil samples before and after 100 hours endurance test (see online version for colours)



Analytical ferrography has also been done to assess the condition of lubricating oil. Ferrograms were developed on the glass substrate and than examined by using bi-chromatic microscope which uses simultaneously reflected red light and transmitted green light. Ferrograms of fresh and used (after 100-hours test) lubricating oil samples are shown in Figure 21. Overall visual inspection of ferrograms show lower particle density hence lower wear for biodiesel-fuelled engine.

4 Conclusions

In general, the biodiesel blends displayed performance characteristics very similar to mineral diesel. Lower blends, especially B20 have shown better performance in terms of power output and efficiency. It is found that CO and HC emissions decreased and NO_x emission increased for the biodiesel blends. Experiments suggest that the combustion starts earlier in case of biodiesel blends compared to diesel. Analysis of pressure time history and heat release analysis indicate that all fuel blends exhibits similar combustion stages as diesel and no undesirable combustion features were observed. In addition, it showed that under all engine operating conditions, heat release always takes place earlier for biodiesel blends compared to diesel. It behaves like combustion advance and one of the reasons for NO_x increase in the engine exhaust of biodiesel-fuelled engine. Based on the endurance test, it is found that biodiesel can overcome most of the operational problems associated with vegetable oil such as injector coking and ring sticking, etc. Less carbon deposits on the in-cylinder parts are observed for 20% biodiesel (B20) blend. Wear metals analysis in lubricating oil samples further shows lower wear for biodiesel-fuelled engine. Pb and Al were found slightly higher for biodiesel-fuelled engine may be due to the attack of biodiesel on paints and bearings. Surface roughness profile and various roughness parameters show that wear is higher at anti-thrust side and the TDC location. Similar wear pattern was found with biodiesel-fuelled engine but lower wear was observed. Overall, biodiesel can be successfully used for partial substitution of mineral diesel. It can readily be adopted as an alternative fuel in the existing CIDI engines with out any major modifications in the engine hardware.

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