Effect of Karanja biodiesel blend on engine wear in a diesel engine

Article *in* Fuel · October 2014

DOI: 10.1016/j.fuel.2014.05.039

2 authors:

Atul Dhar
Indian Institute of Technology Kanpur

Avinash Kumar Agarwal
Indian Institute of Technology Kanpur

Fuel 134 (2014) 81–89

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Effect of Karanja biodiesel blend on engine wear in a diesel engine

Atul Dhar, Avinash Kumar Agarwal *

Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

HIGHLIGHTS

- Effect of B20 and diesel on engine wear in 250 h test.
- Higher carbon deposits in B20 vis-a-vis diesel.
- No adverse effect of B20 on liner surface texture.
- Lower wear of vital components for B20 engine.
- Higher wear of bearings, and crank pin for B20.

ARTICLE INFO

Article history:
Received 24 October 2013
Received in revised form 21 December 2013
Accepted 13 May 2014
Available online 2 June 2014

Keywords:
Wear
Biodiesel
Endurance test
Carbon deposits
Surface roughness

ABSTRACT

For large-scale and reliable implementation of biodiesel in transportation engines, its effects on engine wear and engine durability upon prolonged usage needs to be experimentally investigated. Therefore effects of 20% Karanja biodiesel blend (KOME20) on engine wear and durability was studied vis-à-vis mineral diesel in 250 h long endurance test on a direct injection compression ignition (DICI) engine. Visual inspection of engine components for deposits indicted higher carbon deposits on piston top, cylinder head and injector tip for biodiesel fuelled engine. Relatively lower wear of valves, pistons, piston rings, liners and small end bearings of the connecting rods was observed for biodiesel fuelled engine. Wear of big end bearing of the connecting rods, main bearings and crank pins was found to be higher for biodiesel fuelled engine. Surface texture of cylinder liners remained in acceptable condition after the endurance test for mineral diesel as well as Karanja biodiesel blend. Despite higher carbon deposits and higher wear of some vital engine components, no operational problems were observed during the long-term endurance test for the biodiesel fueled engine.

1. Introduction

Due to dwindling supply of fossil fuels and increasing concerns of global warming and air pollution, alternative fuels are being explored and used globally. Biodiesel is one of the main candidate alternative fuel for partial replacement of mineral diesel with the constraints of slight modifications required in engine hardware/control system, modifications in the fuel production and delivery infrastructure, economic feasibility, etc. [1,2]. Many studies have demonstrated promising potential for biodiesel utilization in conventional diesel engines by evaluating engine performance, emissions and combustion characteristics of biodiesel and its blends in short duration experimental investigations. However, in long-term engine tests, biodiesel is seen to contribute towards formation of engine deposits, degradation of lubricating oils, and plugging of fuel filters, mainly depending on lubricating oil/ fuel degradability, biodiesel's impurity content, cold flow properties, etc. [2–4].

Fazal et al. summarized the comparison of wear of biodiesel and mineral diesel fuelled engines in a review. They suggested either lower or similar wear for biodiesel/biodiesel blend fuelled engines in comparison to mineral diesel fuelled engines, for both static engine as well as field trials [4]. Agarwal et al. concluded from their 512 h long endurance test on a single cylinder engine using 20% blend of linseed oil methyl ester that biodiesel does not have any significant adverse effect on wear of various vital moving components of the engine [5]. Verhaeven et al. reported that there was no significant difference in the wear of the fuel injectors and fuel injection equipment [6], even after 100,000 km field trial with rapeseed oil methyl ester (RME) and used vegetable oil methyl ester (UVOME) as alternate fuels. Sinha et al. reported that physical measurements of various vital engine components showed lower wear for B20 fueled engine in comparison to mineral diesel except big end bearing, which showed slightly higher wear for B20 fueled

* Corresponding author. Tel.: +91 512 2597982; fax: +91 512 2597405.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

http://dx.doi.org/10.1016/j.fuel.2014.05.039
0016-2361/

Table 1
Properties of Karanja biodiesel vis-à-vis mineral diesel.

Property	ASTM 6571 limits for biodiesel	KOME	Diesel
Density (g/cm^3) @ 30 °C	0.8–0.9	0.881	0.831
Viscosity (cSt) @ 40 °C	1.9–6.0	4.41	2.78
Flash point (°C) (min.)	130	168	49.5
Cetane number (min.)	47	50.8	51.2
Conradson carbon residue (%) (max.)	0.05	0.02	0.01
Ash content (%) (max.)	0.02	0.008	0.005
Moisture content (ppm) (max.)	500	<200	<200
Calorific value (MJ/kg)	–	37.98	43.78
Copper corrosiveness	3a	1a	1a
Iodine value	–	83	–
C (%)	–	74.2	87
H (%)	–	12.9	13
N (ppm)	–	3.9	9
O (%)	–	12.8	–
S (ppm) (max.)	15	2	50
Induction period at 110 °C (h) (min)	6	6.2	–

Table 2
Technical specifications of the test engine.

Engine type	Four stroke, in-line, naturally aspirated, water cooled, direct injection, compression ignition SUV engine
Number of cylinders	Four
Compression ratio	18
Combustion system	Direct injection, re-entrant bowl
Bore/stroke	88.9/101.6 mm
Swept volume	2520 cc
Liner type	Cast iron replaceable wet liners
Fuel injection timing	(SOI) 17 ± 1° BTDC
Max. torque	152 Nm @ 1800 rpm
Firing order	1–3–4–2
Oil sump capacity	7.0 l

Table 3
Engine loading cycle for the endurance test.

Speed (rev/m)	Load (N m)	Running time (min)
2600	105	50
1800	135	45
750	No load	5
2600	135	20

compression ignition direct injection (CIDI) engine [7]. Çetinkaya et al. observed the same level of carbon deposits on fuel injectors of the two vehicles fuelled with used cooking oil based biodiesel and mineral diesel in a 7500 km field test in winter conditions [8]. Pehan et al. reported similar carbon deposits in the combustion chambers of biodiesel and diesel fuelled engines [9]. Agarwal et al. reported higher carbon deposits on the piston of preheated Karanja oil and its blends fuelled engine in comparison to mineral diesel fuelled engine in a long-term endurance test [10,11].

There are only handful of studies [4–9,12–14] on the long-term effects of biodiesel on engine wear and engine deposits in comparison to short-term investigations on engine performance, emissions and combustion reported in open literature. Differences in chemical composition of biodiesel and mineral diesel require evaluation of material compatibility of biodiesel with diesel engines during long-term engine operation before the countrywide large-scale implementation of biodiesel as an alternative fuel. Karanja oil is a promising non-edible feedstock for producing biodiesel in India and South Asian region, where this is a commonly found tree species. Karanja oil is seen as a feedstock with a potential of producing biodiesel on large scale because it is well adapted to local climatic conditions and is available in surplus quantities throughout the length and breadth of the South Asian region [11,15]. In this study, effect of 20% blend of Karanja biodiesel with mineral diesel (KOME20) on wear of vital engine components and carbon deposits on the engine components was investigated vis-à-vis baseline mineral diesel in a variable speed medium duty DICI sports utility vehicle (SUV) engine.

2. Methodology

Karanja oil methyl ester (KOME) used in this study was comprehensively characterized for its physical, and thermal properties by measuring its density, viscosity, flash point, cetane number, calorific value, carbon residue, ash content etc. These properties are compared vis-à-vis mineral diesel (Table 1). Table 1 also reports the biodiesel specifications prescribed by ASTM D6571. Density of Karanja biodiesel was relatively higher than mineral diesel however it was within the specified ASTM limits for biodiesel. Viscosity of Karanja biodiesel at 40 °C was also higher than mineral diesel. Cetane numbers of Karanja biodiesel and mineral diesel were

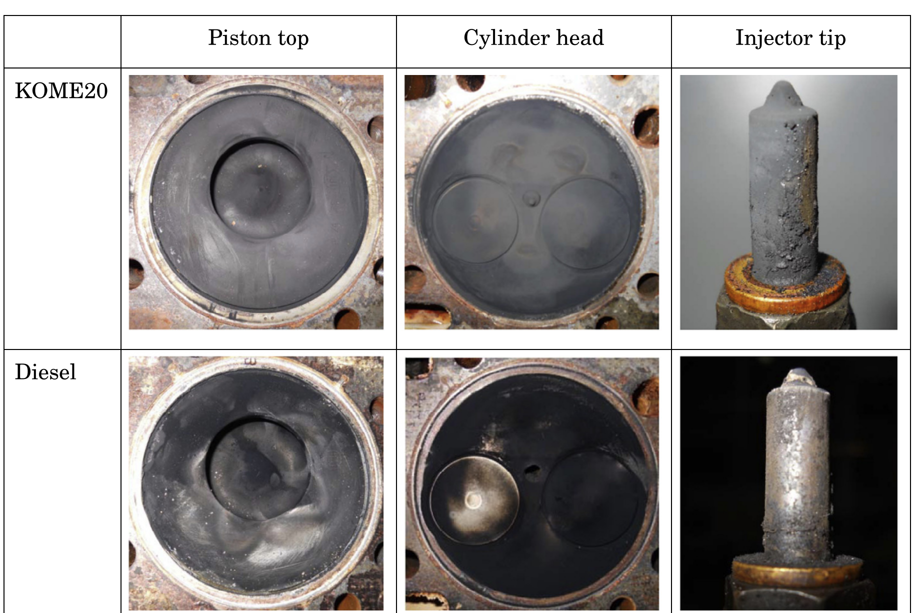


Fig. 1. Carbon deposits on the piston top, cylinder head and injector tip of mineral diesel and KOME20 fuelled engines.

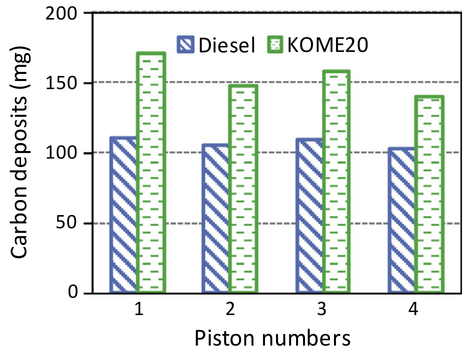


Fig. 2. Carbon deposits on the piston top of mineral diesel and KOME20 fuelled engines.

almost similar. Conradson carbon residue of biodiesel was slightly higher than mineral diesel, which indicates the possibility of higher carbon deposit formation in the combustion chamber. Moisture content of biodiesel was less than 200 ppm, which was also within specified ASTM limits. Calorific value of Karanja biodiesel was 14% lower than mineral diesel. Similar copper corrosiveness grade '1a' of Karanja biodiesel vis-à-vis mineral diesel indicated that it does not have any additional harmful effects on copper containing components of the engine. Karanja biodiesel contains 12.8% oxygen, which causes significant change in the chemical composition of the air-fuel mixture during combustion. Sulfur content of the Karanja biodiesel was lower than mineral diesel.

Effect of KOME20 on the engine wear and durability was experimentally investigated in a four-stroke, four-cylinder, variable speed, medium-duty SUV diesel engine (Mahindra & Mahindra, MDI 3000) during a 250 h endurance test (which is equivalent to roughly 25,000 km vehicle field trial) in two phases for two fuels (KOME20 and mineral diesel). Detailed technical specifications of the test engine are given in Table 2. In first phase, new set of liners, pistons, piston rings, gudgeon pins and bearings were installed and the engine was operated for 250 h on mineral diesel for generating baseline data. After the endurance test, wear of major components and carbon deposits on the vital engine components were recorded. In the second phase, new set of components were installed in the engine and 250 h endurance test was repeated with KOME20 as a fuel for comparing the effect of new fuel on the engine wear and durability vis-à-vis mineral diesel.

During 250 h duration endurance test, engine speed and load were varied according to a 2 h cycle (Table 3) as specified by Indian Standards Code IS: 10000 (Part IX) [16] for testing this variable speed transportation diesel engine.

Dimensions of piston rings were measured by precision digital micrometer. Distance of valve head from the mounting flange face was measured using a precision dial gauge. Close ring gap was measured by precision slip gauge. Crank pin diameter, gudgeon pin diameter and connecting rod small end bush diameter, and piston diameter were measured by precision Vernier caliper. Cylinder liner bore, big end bearing bore, and main bearing bore were measured by precision bore gauges. Wear of piston rings was characterized by weight loss using a micro-balance. Roughness profiles of cylinder liner surfaces were evaluated by surface profilometer (Mitutoyo Corporation; SJ-301). Roughness profiles were taken for an evaluation length of 4 mm at 20× magnification in the horizontal direction and 2000× magnification in the vertical direction. Surface profiles were taken at three liner locations namely, top dead center (TDC) (where first compression ring reversal takes place, 15–19 mm below the top edge of the cylinder liner), mid-stroke (59–63 mm below the top edge of the cylinder liner) and at the bottom dead center (BDC) (103–107 mm below the top edge of the cylinder liner). After the completion of the endurance test, circular liner segments were cut from TDC, mid-stroke and BDC locations and scanning electron microscopy (SEM) images of these pieces were taken using field emission scanning electron microscope (FE-SEM) (Carl Zeiss NTS GmbH; SUPRA 40VP). Images were taken at 300X magnification. One piece was cut from a fresh liner for baseline reference surface roughness. The surface profiles and

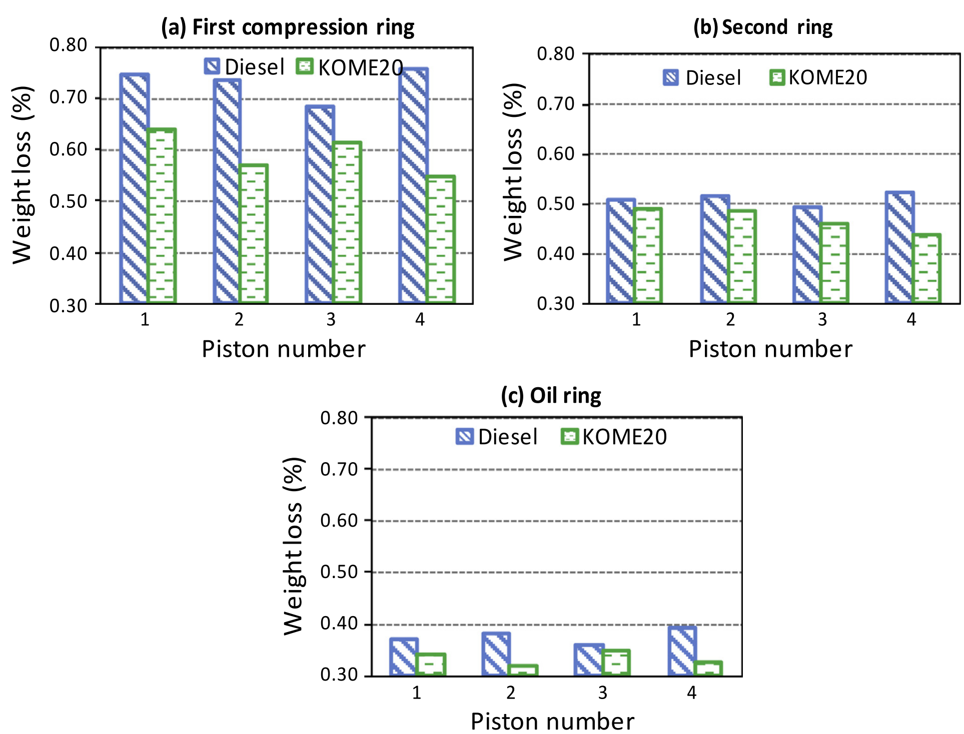


Fig. 3. Comparison of piston ring weight loss due to wear for (a) first compression ring (b) second ring and (c) the oil ring of mineral diesel and KOME20 fuelled engines.

SEM images were taken for both, thrust (T) and anti-thrust (AT) sides of the liner at all three locations mentioned above.

3. Results and discussion

3.1. Carbon deposits

In-cylinder components of DICI engine working under close tolerances were subjected to high thermal and mechanical stresses during the long-term endurance test. Carbon deposits on important engine parts were evaluated after 250 h endurance test for each of the fuels. Carbon layer deposited on piston top, injector tip and cylinder head of KOME20 fuelled engine was comparatively thicker as seen in Fig. 1. Large white marks on the exhaust valves were seen due to thermal stresses experienced by theses valves. Carbon deposits on the injector tips were also higher for KOME20 fuelled engine than mineral diesel fueled engine's injector.

Sinha and Agarwal [7] reported lower deposits for B20 (rice-bran biodiesel) in comparison to mineral diesel during a 100 h endurance test. Higher cetane number of rice-bran biodiesel in comparison to Karanja biodiesel results in higher in-cylinder temperatures due to advanced combustion phasing, which possibly causes comparatively higher reduction in carbon deposits for rice-bran biodiesel.

The deposited carbon on the piston top was carefully removed and weighed for quantification of deposits. Fig. 2 shows the amount of carbon deposits on the piston top of mineral diesel and KOME20 fuelled engines.

Weight of carbon deposits was higher for KOME20 fuelled engine in comparison to mineral diesel. Fuel characterization showed higher conradson carbon residue for Karanja biodiesel (0.02%) compared to mineral diesel (0.01%), which causes higher residual carbon deposits in the combustion chamber after the combustion of Karanja biodiesel blend. Lower volatility of Karanja biodiesel also increased the heat release during late combustion phase (Fig. 4). Soot particles formed, during late combustion phase get lesser time for oxidation, accompanied by poor volatility of KOME, resulting in condensation of unburned/pyrolysed fuel on the combustion chamber components. Incomplete combustion of these fuels is responsible for increase in carbon deposits for KOME20 fuelled engine.

3.2. Physical wear of vital engine components

Dimensions of valves, liners, pistons, piston rings, gudgeon pins and bearings were measure according to IS: 10000 (Part V) [17] before and after the completion of endurance test for estimating engine wear in each phase of the experiment. In the first phase,

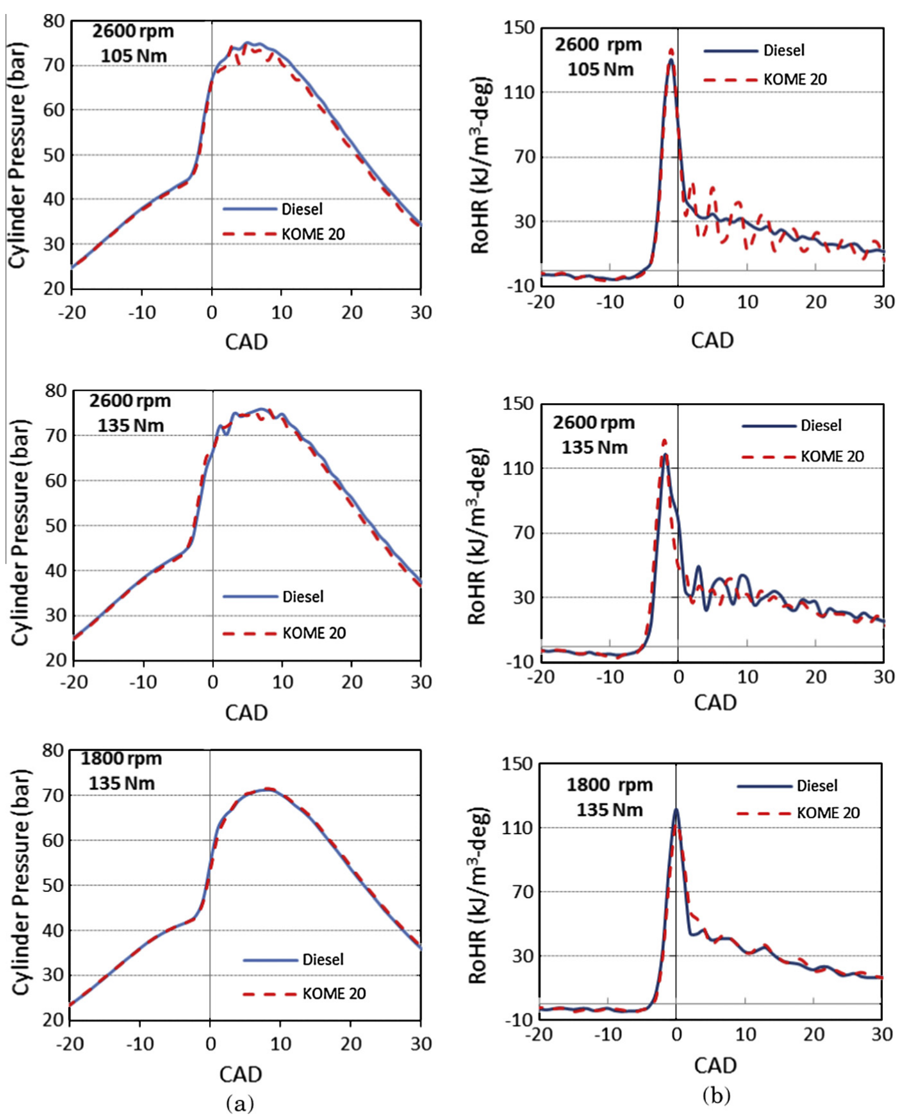


Fig. 4. Comparison of (a) cylinder pressure and (b) rate of heat release variation with crank angle degree for mineral diesel and KOME20 at operating conditions of endurance test cycle.

Table 4
Comparison of physical wear of vital engine components of mineral diesel and KOME20 fuelled engines.

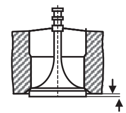
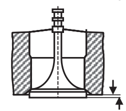
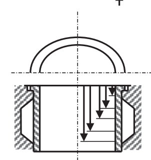
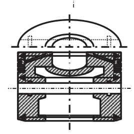
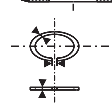
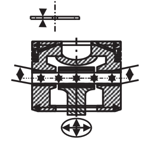
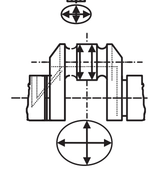
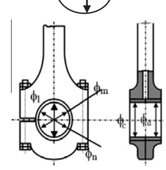
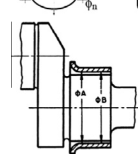
Component		Percentage difference in wear of components for KOME20 w.r.t. mineral diesel fuelled engine (L: lower; H: higher)
Distance of inlet valve head from mounting flange face		10 (L)
Distance of exhaust valve head from mounting flange face		55.5 (L)
Liner bore		20.5 (L)
Piston diameter		49.5 (L)
Piston rings		24.8 (L)
Gudgeon pin, pin bore, small end bush of connecting rod		10.8 (L)
Crank pin		26.5 (H)
Connecting rod bearing bore diameter		45.16 (H)
Main bearing bore diameter		92.0 (H)

Table 5
Comparison of peak cylinder pressure and peak rate of pressure rise for mineral diesel and KOME20.

Speed (rpm)	Load (N m)	Peak pressure (bar)		Peak rate of pressure rise (bar/deg.)	
		Diesel	KOME20	Diesel	KOME20
2600	105	77.9	77.2	11.0	11.5
2600	135	78.8	78.9	10.9	11.2
1800	135	71.9	72.1	8.7	8.1

mineral diesel and in the second phase, KOME20 were used as fuel, while keeping all other operating conditions identical for both phases, in order to estimate the effect of KOME20 on engine wear vis-a-vis baseline mineral diesel.

Wear of inlet and exhaust valves was estimated by measuring the distance of mounting flange face before and after the endurance test. It was observed that wear of inlet valve was 10% lower for KOME20 fuelled engine in comparison to mineral diesel (Table 4). Wear of exhaust valve was also lower for KOME20, possibly due to slightly lower exhaust gas temperature experienced in KOME20 fuelled engine. Wear of cylinder liners, pistons, and piston rings were lower for KOME20 fuelled engine possibly due to higher lubricity of biodiesel and lower in-cylinder temperatures. Lower wear of piston rings was also confirmed by estimating the wear of piston rings (by measuring weight loss of piston rings after the endurance test) (Fig. 3). In vehicle trials for 100,000 km were executed for mineral diesel and soybean biodiesel blend (B5) by Ferrarese et al. and they reported higher wear of

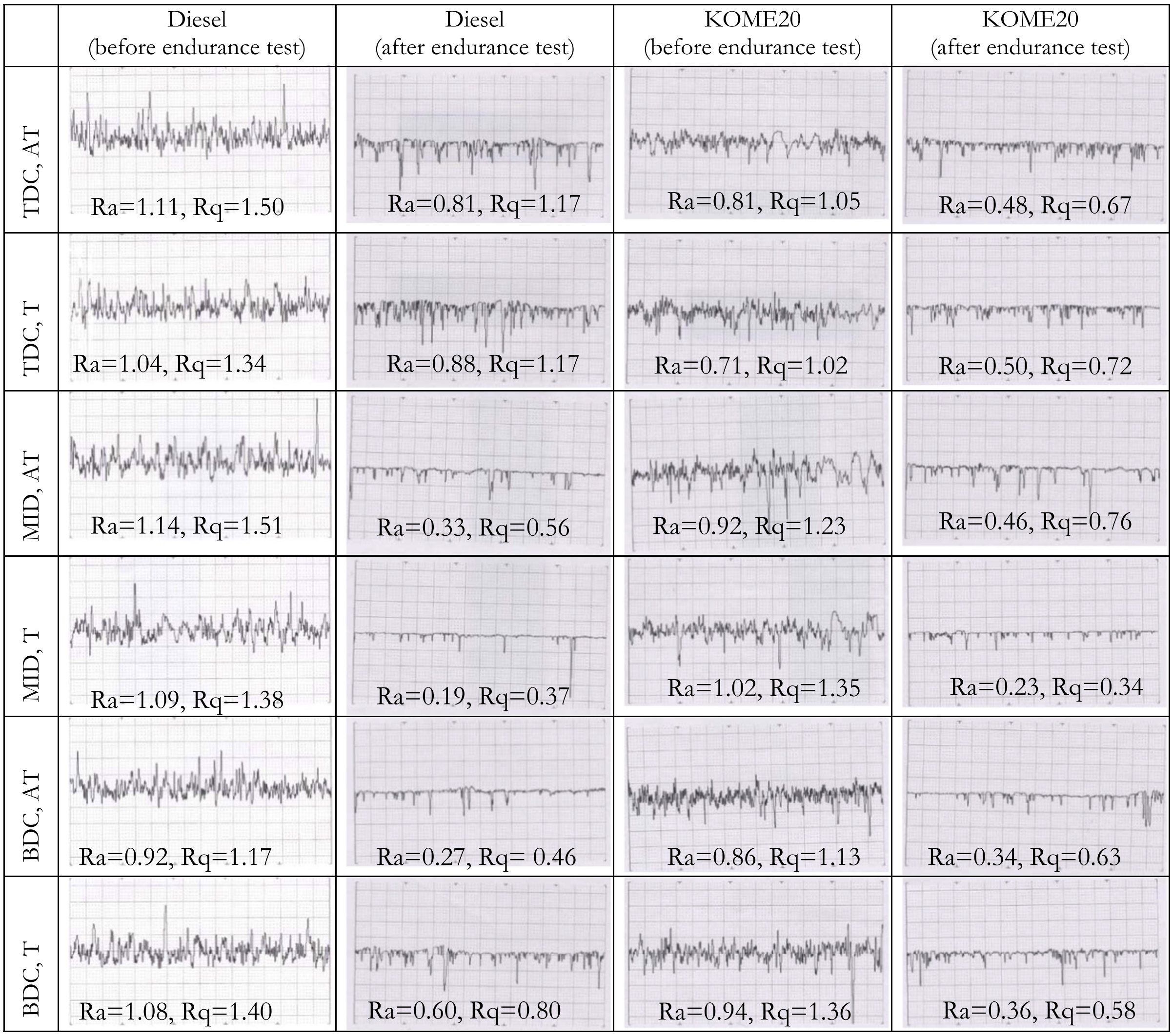


Fig. 5. Liner surface roughness profiles of mineral diesel and KOME20 fuelled engines.

the top ring and cylinder bore with B5 compared to components tested with mineral diesel [18]. Wear of small end of the connecting rod was also slightly lower for KOME20 fuelled engine. Higher wear of crank pin diameter, big end bearing and main bearing was observed for KOME20 fuelled engine (Table 4). Ferrarese et al. also reported that performance of soybean biodiesel blend (B5) was adequate but corrosion marks on the connecting rod bearing of castor biodiesel were observed [18]. Bearing of these components is directly related to the quality of lubrication. Higher wear of these components indicated possibility of adverse effect of KOME20 on the lubricating oil.

Change in wear of engine during long duration endurance test may occur due to differences in mechanical stress, thermal stress and chemical reactivity of mineral diesel and KOME20. For quantifying the effect of mechanical and thermal stresses, variations in cylinder pressure and rate of heat release for engines fuelled with diesel and KOME20 is compared in Fig. 4 at operating points of the endurance test cycle (Table 3). Due to very small difference in combustion related properties of Karanja biodiesel (KOME) and diesel (which further reduce when properties of KOME20 and diesel are compared), variation of cylinder pressure and rate of heat release with crank angle degree are almost identical for KOME20 and mineral diesel. Comparatively higher fluctuations were observed in mixing controlled combustion phase as well as late combustion phase of the heat release curve at operating condition corresponding to higher engine speed and lower load for KOME20, which indicates possibility of relatively inferior combustion in KOME20 fuelled engine due to lower volatility and inferior fuel-air mixing characteristics of KOME20 in comparison to mineral diesel. At higher engine loads, these trends disappear due to higher in-cylinder temperatures, which improve the evaporation and mixing characteristics of low volatility fuel. Table 5 indicates that difference in peak cylinder pressures and pressure rise rates are insignificant for KOME20 and mineral diesel fuelled engines during endurance test. This shows that difference in engine wear is mainly caused by higher chemical reactivity of KOME, which enhances lubricating oil degradation. This lubricating oil degradation results in higher wear of bearings and crank pin.

3.3. Cylinder liner surface wear

Wear of cylinder liner surface was characterized by measuring the roughness profiles of cylinder liner at TDC, mid-stroke and BDC positions on the thrust and anti-thrust sides of the liner, before and after the endurance test. Average roughness (R_a) value of roughness profiles represents the arithmetic average of roughness profile over the total evaluation length. R_q value of roughness profiles represents the root mean square average of roughness profile over the total

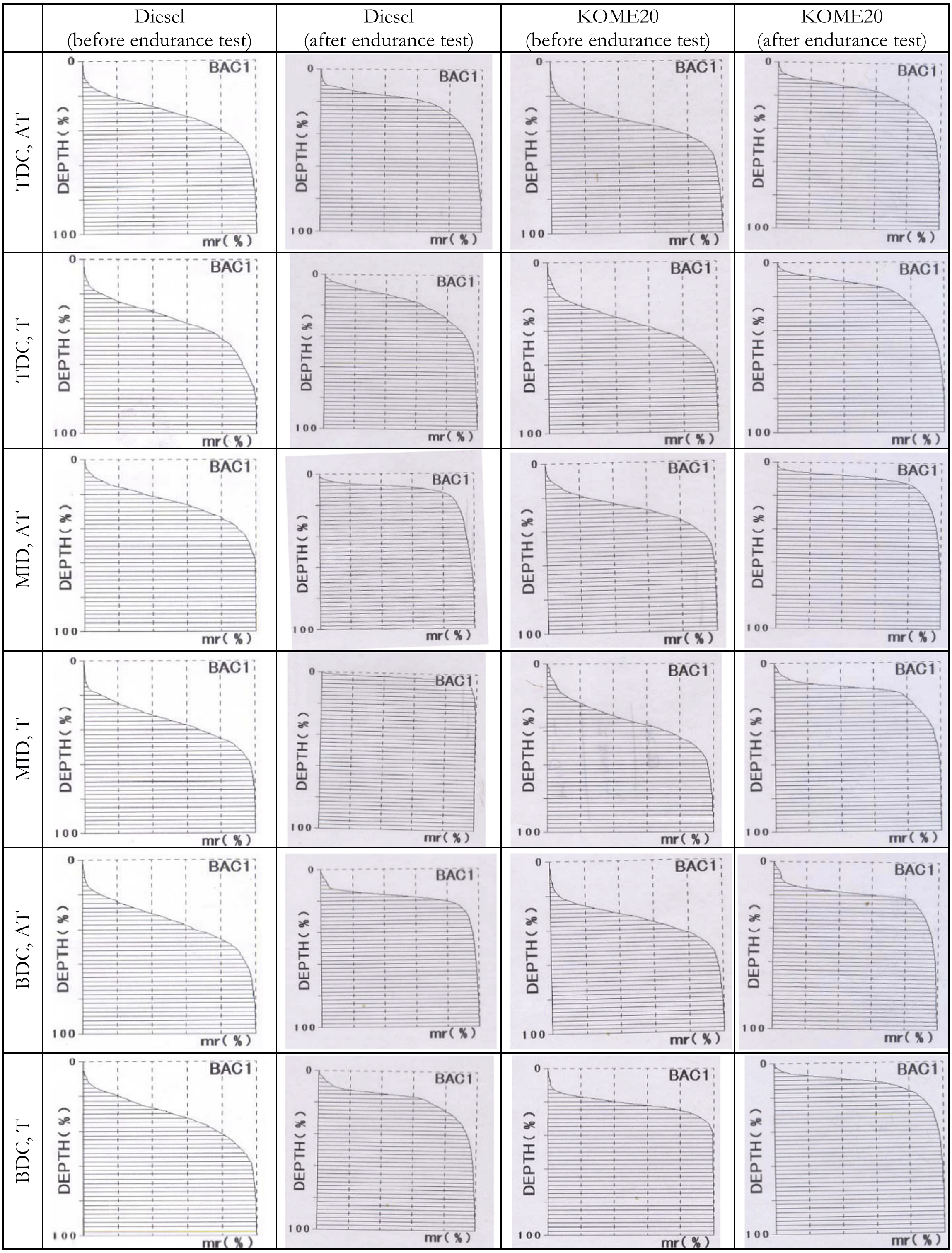


Fig. 6. Liner surface bearing area curves of mineral diesel and KOME20 fuelled engines.

evaluation length. These profiles with R_a and R_q values are shown in Fig. 5. Wear was qualitatively and quantitatively estimated by difference in roughness profiles before and after the endurance test.

Anti-thrust side of the liner is subjected to abrasion in three out of four strokes of piston motion during an engine cycle, including expansion and compression strokes (which also have high pressure and temperature), hence higher wear is observed as expected on the anti-thrust side of the liner [19]. Wear of mineral diesel and KOME20 fuelled liners was comparable at all measured locations. Bearing area curves are a useful measure for describing wear pattern of liner surface. Bearing area curves represent the material ratio of the profile as a function of the slice level, when slicing the material at a certain height [20–22]. Bearing area curves of mineral diesel and KOME20 fuelled engine liners are shown in Fig. 6. After the wearing out of liner surfaces, bearing area curves become flatter, indicating removal of peaks of the honing marks. Shapes of bearing area curves indicate similar nature of wear for KOME20 and mineral diesel fuelled engine liners.

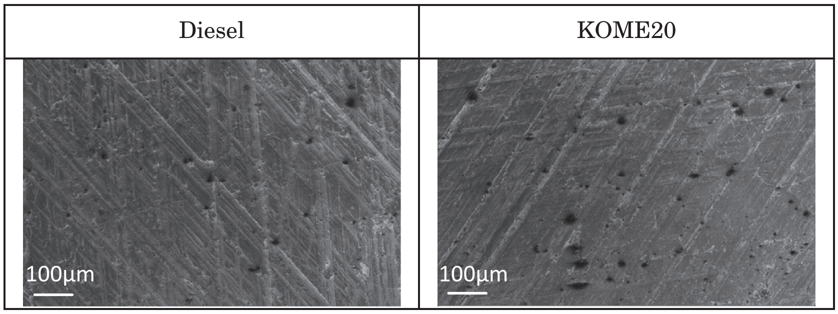


Fig. 7. SEM images of fresh liner (magnification 300×) of mineral diesel and KOME20 fuelled engines.

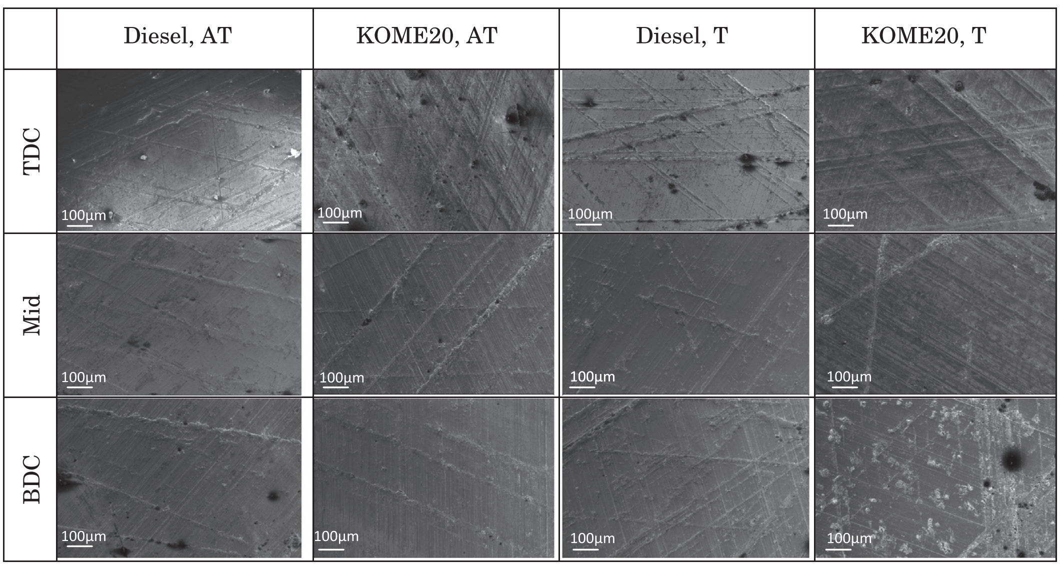


Fig. 8. SEM images of liner surface after endurance test (300× magnification) for mineral diesel and KOME20 fuelled engines.

SEM images of the liners at the TDC, mid-stroke and BDC positions at thrust and anti-thrust sides were taken for assessing the surface condition of the liners after completion of the endurance test. Fig. 7 shows the images of liners below the BDC location (where no wear takes place due to no contact with the rings, therefore representing fresh liner) on the thrust side after 250 h endurance test. This image has been used as a representative image for fresh liner surface condition in order to compare the condition of worn liner surface (due to abrasive action of piston rings at TDC, mid-stroke and BDC positions).

Honing marks are clearly visible in fresh liners (Fig. 7). Fig. 8 shows the SEM images at TDC, mid-stroke and BDC positions at thrust side (T) and anti-trust side (AT) for mineral diesel and KOME20 fuelled engines. At BDC position of KOME20 fuelled engine liner, white spots were observed, which were most probably due to corrosive wear. Wear trace metals and ash content measurements of used lubricating oil also indicated higher metal debris concentration in the lubricating oil samples drawn from KOME20 fuelled engine. On the anti-thrust side, scratch marks were visible along with honing grooves for KOME20 fuelled engine's liner. Overall, for both fuels, surface texture of the cylinder liners was in acceptable condition even after the completion of 250 h endurance test.

4. Conclusions

Effect of 20% Karanja biodiesel blend on engine wear and durability was experimentally investigated vis-à-vis baseline mineral diesel in a 250 h long-term endurance test. Visual inspection of engine components for deposits indicted higher carbon deposits on piston top, cylinder head and injector tip for KOME20 fuelled engine. Weight of carbon deposits on the pistons of biodiesel fuelled engine was also higher than mineral diesel fuelled engine. Physical wear measurement of engine components showed lower wear of valves, pistons, piston rings, liners and small end bearing of the connecting rods for biodiesel fuelled engine. Higher wear for big end bearing of the connecting rods, main bearings and crank pins was observed for KOME20 fuelled engine. Characterization of liner surface wear shows that for both fuels, surface texture of cylinder liners remained in acceptable condition even after 250 h endurance test. Despite higher carbon deposits and higher wear of few vital engine components, no operational problems were observed during 250 h endurance test for KOME20 fuelled engine in comparison to mineral diesel fuelled engine. Hence, biodiesel blends with 20% or lower biodiesel concentration may be used in an unmodified DICI SUV engines. However, further detailed investigation of the effect of biodiesel properties on the composition and property degradation of the lubricating oil as well as engine combustion is required. These factors are primarily responsible for carbon deposits formation and wear of engine components and are therefore vital for large-scale implementation of biodiesel in transportation engines successfully.

Acknowledgements

Research grant from Shell Global Solutions, Netherlands and Shell Technology India Private Limited, Bangalore for conducting this research is gratefully acknowledged.

References

[1] Nigam PS, Singh A. Production of liquid biofuels from renewable resources. Prog Energy Combust Sci 2011;37:52–68.
[2] Agarwal AK, Singh SK, Shukla MK. Effect of EGR on the exhaust gas temperature and exhaust opacity in compression ignition engines. Sadhana-Acad Proc Eng Sci 2004;29(3):275–84.
[3] Lapuerta M, Armas O, Fernàndez JR. Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;34:198–223.
[4] Fazal MA, Haseeb ASMA, Masjuki HH. Biodiesel feasibility study: an evaluation of material compatibility; performance; emission and engine durability. Renew Sustain Energy Rev 2011;15:1314–24.
[5] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engines. ASME J Eng Gas Turbines Power 2001;123:440–7.
[6] Verhaeven E, Pelkmans L, Govaerts L, Lamers R, Theunissen F. Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles. SAE paper 2005; 2005-01-2201.
[7] Sinha S, Agarwal AK. Experimental investigation of the effect of biodiesel utilization on lubricating oil degradation and wear of a transportation CIDI engine. J Eng Gas Turbines Power 2010;132:042801-1–1-9.
[8] Çetinkaya M, Ulusoy Y, Tekìn Y, Karaosmanoũlu F. Engine and winter road test performances of used cooking oil originated biodiesel. Energy Convers Manage 2005;46:1279–91.
[9] Pehan S, Jerman MS, Kegl M, Kegl B. Biodiesel influence on tribology characteristics of a diesel engine. Fuel 2009;88:970–9.
[10] Agarwal AK, Dhar A. Karanja oil utilization in DI engine by preheating: experimental investigations of engine durability and lubricating oil properties part II. Proc IMechE Part D: J Aut Eng 2009;224:85–97.
[11] Agarwal AK, Dhar A. Wear, durability, and lubricating oil performance of a straight vegetable oil (Karanja) blend fueled direct injection compression ignition engine. J Renew Sustain Energy 2012;4(6):063138-1–063138-13.
[12] Haseeb ASMA, Fazal MA, Jahirul MI, Masjuki HH. Compatibility of automotive materials in biodiesel: a review. Fuel 2011;90(3):922–31.
[13] Armas O, Martínez-Martínez S, Mata C. Effect of an ethanol–biodiesel–diesel blend on a common rail injection system. Fuel Process Technol 2011;92(11):2145–53.
[14] Liaquat AM, Masjuki HH, Kalam MA, Fazal MA, Khan AF, Fayaz H, et al. Impact of palm biodiesel blend on injector deposit formation. Appl Energy 2013;111:882–93.
[15] Dhar A, Agarwal AK. Performance, emissions and combustion characteristics of Karanja biodiesel in a transportation engine. Fuel 2014;119(1):70–80.
[16] Indian standard IS: 10000, Method of tests for internal combustion engine: Part IX, Endurance tests. Bureau of Indian Standards. India: New Delhi; 1980.
[17] Indian standard IS: 10000, Method of tests for internal combustion engine: Part V, Preparation for tests and measurements for wear. Bureau of Indian Standards. India: New Delhi; 1980.
[18] Ferrarese A, Uehara S. Influence of biodiesel on powercell components. SAE paper 2009-01-0491; 2009.
[19] Dong WP, Davis EJ, Butler DL, Stout KJ. Topographic features of cylinder liners-an application of three-dimensional characterization techniques. Tribol Int 1995;28:453–63.
[20] Srivastava DK, Agarwal AK, Kumar J. Effect of liner surface properties on wear and friction in a non-firing engine simulator. Mater Des 2007;28:1632–40.
[21] Kumar R, Kumar S, Prakash B, Sethuramiah A. Assessment of engine liner wear from bearing area curves. Wear 2000;239:282–6.
[22] Agarwal D, Singh SK, Agarwal AK. Effect of exhaust gas recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine. Appl Energy 2011;88(8):2900–7.