Karanja oil utilization in a direct-injection engine by preheating. Part 1: experimental investigations of engine performance, emissions, and combustion characteristics

A K Agarwal*[*] and **A Dhar**
Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, India

The manuscript was received on 18 May 2009 and was accepted after revision for publication on 30 June 2009.

DOI: 10.1243/09544070JAUTO1266

Abstract: Vegetable oils have an energy content suitable for use as a fuel in diesel engines. Some of these oils have already been evaluated as substitutes for diesel fuels. However, several operational and durability problems of using straight vegetable oils in diesel engines have been reported in the literature, caused by their relatively higher viscosity and low volatility compared to mineral diesel. This viscosity can be brought into the acceptable range by transesterification, by blending of vegetable oil with diesel, or by preheating the vegetable oil using the waste heat of exhaust gases. The reduction in the viscosity by blending or exhaust gas preheating saves the processing cost incurred in the transesterification process involving expensive chemicals.

Experimental investigations were carried out for the combustion, performance, and emission characteristics of heated Karanja oil in a direct-injection compression ignition engine at different loads at a constant engine speed of 1500 r/min. Analysis of the cylinder pressure rise, instantaneous heat release, and cumulative heat release was carried out. Combustion phasing of preheated Karanja oil was found to be identical with that of mineral diesel. Heating the vegetable oil substantially reduces the combustion duration. The brake specific fuel consumption and exhaust gas temperatures for heated Karanja oil were found to be higher than mineral diesel. The thermal efficiency was slightly lower for heated Karanja oil than for diesel. The carbon dioxide, carbon monoxide, hydrocarbon, and nitric oxide emissions were lower for heated Karanja oil than for diesel.

Keywords: Karanja oil, performance, mass emissions, combustion characteristics, rate of heat release, biofuels

1 INTRODUCTION

Energy insecurity caused by depleting petroleum resources and environmental problems posed by fossil fuels have generated urgency in the search for alternative renewable compression ignition (CI) engine fuels. Finding an alternative fuel for diesel is critically important for the nation's economy and security. Substitution of oil imports for the transportation and agricultural sectors is the largest and toughest challenge for developing nations such as India. Consideration of non-edible oil seeds as a source of diesel substitute oil is very promising for economic as well as environmental benefits. Among the non-edible oil species, Karanja, Neem, Jatropha, and Mahua are the prominent resources from this perspective [**1**].

Alternative fuels should be easily available, environment friendly and techno-economically competitive. Successful alternative fuels should fulfil environmental and energy security needs without sacrificing engine operating performance [**2**]. Renewable resources offer the opportunity to tap local and renewable resources and to reduce dependence on imported energy resources. For the developing

---

[*] *Corresponding author: Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India.*
email: akag@iitk.ac.in

countries of the world, fuels of bio-origin provide a feasible solution to the twin crises of fossil fuel depletion and environmental degradation. Vegetable oil is a promising alternative fuel for the CI engine because it is renewable, environment-friendly, and easily produced in rural areas. The use of non-edible vegetable oils when compared with edible oils is very significant in developing countries because of the tremendous demand for edible oils as food, and they are far too expensive to be used as fuel at present. Karanja is a native South Asian plant of the western ghats (India) and is mainly found along the banks of streams and rivers or near sea coast and tidal forests. It is well adapted to all soil types and climatic requirements and grows in dry places far in the interior, up to an elevation of 1000 m. It resists drought well and is moderately forest hardy and highly tolerant to salinity. It is a shade bearer tree and is considered to be a good tree for planting in pastures, as grass grows well in its shade [**3**].

Vegetable oils can be used directly or blended with diesel to operate CI engines. Use of blends of vegetable oils with diesel has been carried out successfully by various researchers in several countries [**1**, **4–21**]. It has been reported that use of 100 per cent vegetable oil is also possible with minor fuel system modifications [**11**, **21**, **22**]. Short-term engine performance tests have indicated good potential for most vegetable oils as fuel. The use of vegetable oil results in increased volumetric fuel consumption and brake specific fuel consumption (BSFC). Emissions of carbon monoxide (CO) and hydrocarbons (HCs) were found to be higher, whereas nitrogen oxide (NO_x) and particulate emission were lower than for mineral diesel [**4–23**].

Undoubtedly, transesterification is the well-accepted and best-suited method of utilizing vegetable oils in a CI engine without significant long-term operational and durability issues. However, this adds extra cost of processing because of the transesterification reaction involving chemical and process heat inputs. In rural and remote areas of developing countries, where grid power is not available, vegetable oils can play a vital role in decentralized power generation for irrigation, agriculture, and electrification. In these remote areas, different types of vegetable oil are produced locally but it may not be possible to process them chemically because of logistics problems in rural settings. Hence using heated or blended vegetable oils as petroleum fuel substitutes is an attractive proposition. Keeping these facts in mind, a set of engine experiments were conducted using Karanja oil in an engine of the type typically used for agriculture, irrigation, and decentralized electricity generation.

Preheating was used to lower the viscosity of Karanja oil in order to eliminate various operational difficulties. The present research is aimed at exploring the technical feasibility of Karanja oil in a direct-injection CI engine by utilizing the waste heat of exhaust gases.

2 EXPERIMENTAL SET-UP

A four-stroke, single-cylinder, constant-speed, water-cooled, direct-injection, diesel engine (Kirloskar Oil Engines Ltd. India, model DM-10) was used to study the effect of different Karanja oil conditions on the performance, emissions, and combustion characteristics of the engine (Fig. 1). The detailed specifications of the engine is given in Table 1. The engine was operated at a constant speed of 1500 r/min. The inlet valve opens 4.5° before top dead centre (TDC) and closes 35.5° after bottom dead centre (BDC). The exhaust valve opens 35.5° before BDC and closes 4.5° after TDC. The fuel injection pressure recommended by the manufacturer is 200–205 bar. The oil sump was filled with fresh lubricating oil before beginning the experiments. This engine consists of a gravity-fed fuelling system with an efficient paper element filter, force-fed lubrication for the main bearing, large-end bearings, camshaft bush, and a run-through or thermo-siphon cooling system. Two diesel fuel filters were used for all fuels. The combustion system of this engine is similar to those used in direct-injection automotive engines; i.e. it has a bowl-in-piston type of combustion chamber, a three-hole fuel injector with a nozzle opening pressure of 20 MPa, and a single-fuel-injection event with nozzle opening controlled by a camshaft.

A piezoelectric pressure transducer (Kistler Instruments, Switzerland, model 6613CQ09-01) was installed in the engine cylinder head to acquire the combustion pressure–crank angle history. Machining for installation of the pressure transducer was carried out in the cylinder head and the engine main shaft was coupled to a precision shaft encoder (Encoder India Limited, Faridabad, India, model ENC58/6-720ABZ/5-24V). Signals from the pressure transducer were amplified using a charge amplifier (Kistler Instruments, Switzerland, model 5015A charge meter). The high-precision shaft encoder was used to deliver signals of the crank angle with a resolution of 0.5° crank angle. A TDC marker was used to locate the TDC position in every cycle of the

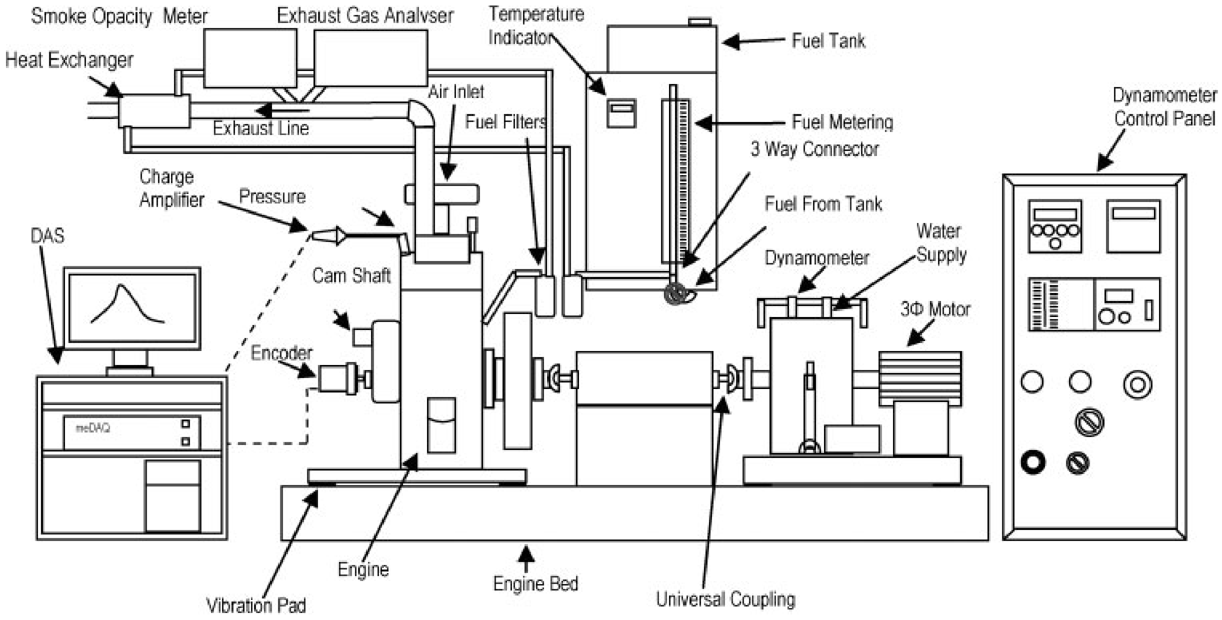


Fig. 1 Schematic diagram of the experimental set-up

Table 1 Engine specifications

Engine parameter	Specification
Manufacturer	Kirloskar Oil Engines Ltd, India
Engine type	Vertical four-stroke single-cylinder constant-speed direct-injection CI engine
Rated power	7.4 kW at 1500 r/min
Bore	102 mm
Stroke	116 mm
Displacement volume	0.948 l
Compression ratio	17.5
Start of fuel injection timing	26° before TDC
Nozzle opening pressure	200–205 bar
Cooling type	Water cooling
Length	685 mm
Width	532 mm
Height	850 mm
Brake mean effective pressure (BMEP) at 1500 r/min	6.34 bar (maximum)
Lubricating oil sump capacity	3.7 l

engine. The signals from the charge amplifier, TDC marker, and shaft encoder were acquired using a high-speed data acquisition system (Hi-Techniques, USA, model meDAQ). Engine tests were performed at 1500 ± 3 r/min, with a fuel injector pressure of 200 bar for diesel, unheated Karanja oil, and preheated Karanja oil. The six engine load conditions where the combustion data were acquired were 0 per cent, 20 per cent, 40 per cent, 60 per cent, 80 per cent, and 100 per cent (47 N m) of the rated load. The cylinder pressure data were acquired for 50 consecutive cycles and then averaged in order to eliminate the effect of cycle-to-cycle variations. All tests were carried out after thermal stabilization of the engine.

The exhaust gas opacity was measured using a smoke opacimeter (AVL Austria, model 437). The exhaust gas composition was measured using an exhaust gas analyser (AVL India, model DIGAS 444); this measures the carbon dioxide (CO_2), CO, HC, and nitric oxide (NO) concentrations in the exhaust gas.

A shell-and-tube type heat exchanger was designed to preheat the vegetable oil using the waste heat of the exhaust gases. The heat exchanger consists of one inner pipe and an outer shell. Fins were brazed to the inner pipe to increase the heat transfer area between the two fluids (vegetable oil and exhaust gases). One supply pipe connection is provided in each side plate of the heat exchanger for the inlet and outlet of the vegetable oil. A thermocouple was provided in the heat exchanger to measure the temperature of the heated vegetable oil, close to the exit point. The temperature of the

Karanja oil was maintained at 100 °C at the exit of the heat exchanger. The flow of exhaust gas to the heat exchanger was regulated by a bypass valve which in turn regulated the temperature of oil at the heat exchanger exit.

3 RESULTS AND DISCUSSION

The important properties of the Karanja oil used in the study are compared with those of mineral diesel in Table 2. All the performance, combustion and emission tests were carried out at an optimum fuel injection pressure (200 bar) for minimum BSFC, thermal efficiency, and smoke opacity for both the fuels for this engine.

3.1 Performance and emissions test

Experiments were conducted using heated and unheated Karanja oil and mineral diesel. The BSFCs for both heated and unheated Karanja oil are higher than those of mineral diesel (Fig. 2). The thermal efficiency shows a significant improvement after preheating the oil (Fig. 3). The oxygen present in the fuel molecules improves the combustion characteristics but the higher viscosity and poor volatility of vegetable oils lead to their poor atomization and combustion characteristics. Preheating reduces the viscosity which results in better atomization and combustion of fuel. Therefore, the BSFC is reduced owing to preheating of the fuel.

The lowest CO_2 emissions were observed for preheated Karanja oil (Fig. 4). The CO_2 emissions for unheated Karanja oil were somewhat higher than for mineral diesel but improvement in combustion due to preheating results in CO_2 reduction. The emissions of CO increase with increasing load (Fig. 5). The higher the load, the richer the fuel–air mixture burned, and thus more CO is produced owing to lack of oxygen. At lower loads, CO emissions for both unheated and preheated Karanja oil are close to those of mineral diesel. At higher loads, preheated Karanja oil shows a significant reduction in CO emission. Preheated and unheated Karanja oil

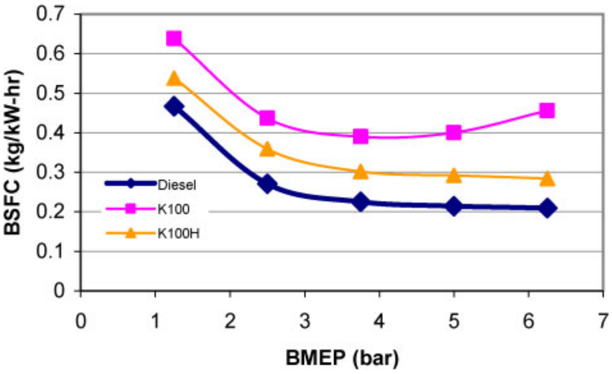


Fig. 2 Comparison of the BSFC values of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

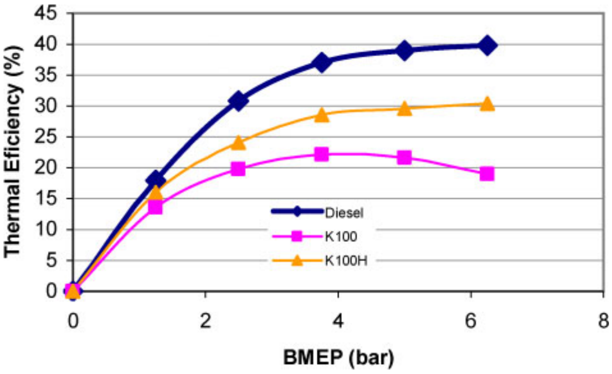


Fig. 3 Comparison of the thermal efficiencies of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

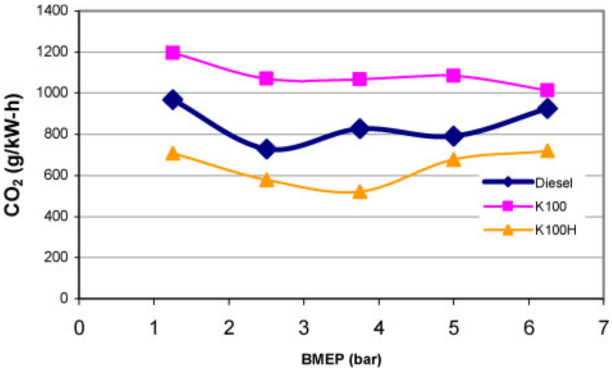


Fig. 4 Comparison of the CO_2 emissions of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

Table 2 Important properties of diesel and Karanja oil

	Value for the following		
Property	Diesel	Karanja oil	Karanja oil (preheated at 100 °C)
Density (kg/m^3)	833.7	938.2	—
Kinematic viscosity at 40 °C (cSt)	2.71	35.98	5.15
Flash point (°C)	48	237	237
Calorific value (MJ/kg)	43.06	41.66	41.66

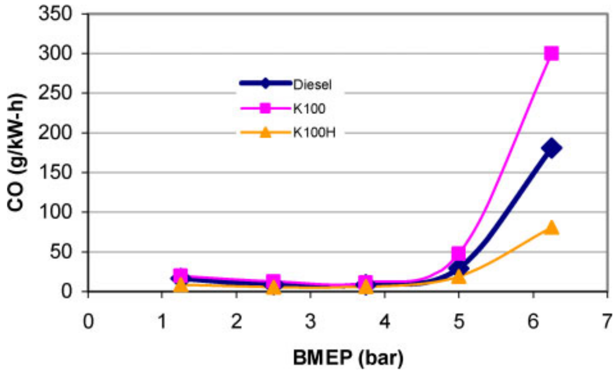


Fig. 5 Comparison of the CO emissions of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

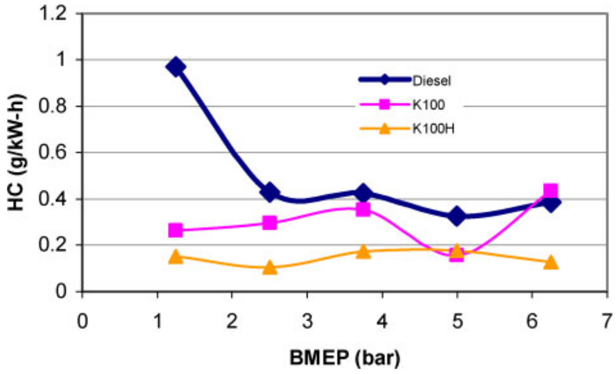


Fig. 6 Comparison of the HC emissions of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

exhibit significantly lower HC emissions compared with mineral diesel (Fig. 6). Even the HC emissions were found to have improved by preheating the Karanja oil.

The smoke opacity for Karanja oil was higher than mineral diesel at lower loads but lower than mineral diesel at higher loads (Fig. 7). The exhaust gas temperatures for both oil conditions were higher than mineral diesel. This difference in exhaust gas temperatures further increases with increasing load (Fig. 8). The NO emission was lowest for heated Karanja oil for all the fuels and highest for unheated Karanja oil (Fig. 9).

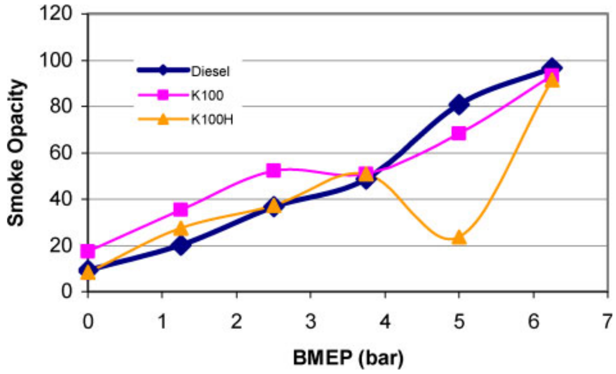


Fig. 7 Comparison of the smoke opacities of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

3.2 Combustion analysis

3.2.1 In-cylinder pressure versus crank angle diagram

The variations in the in-cylinder pressure with crank angle for heated and unheated Karanja oil at different engine operating conditions compared with baseline data of mineral diesel are shown in Fig. 10. From Fig. 10, it can be seen that, at low engine loads, the pressure trends are almost similar for the three fuels. Heated Karanja oil shows an early pressure rise with respect to the mineral diesel. Unheated Karanja oil shows a delayed pressure rise in comparison with

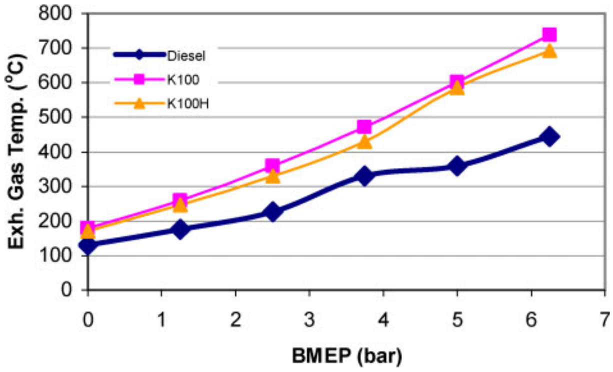


Fig. 8 Comparison of the exhaust gas temperatures of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

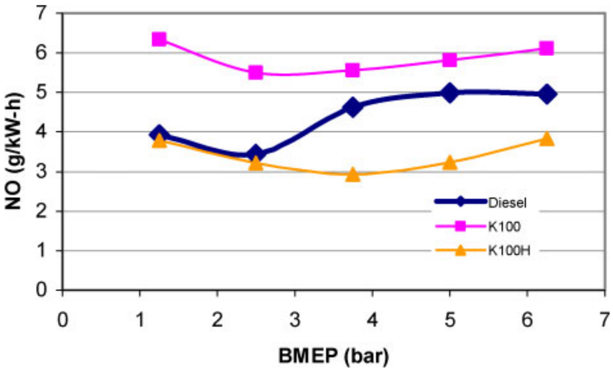


Fig. 9 Comparison of the NO emissions of unheated Karanja oil (K100), preheated Karanja oil (K100H), and diesel

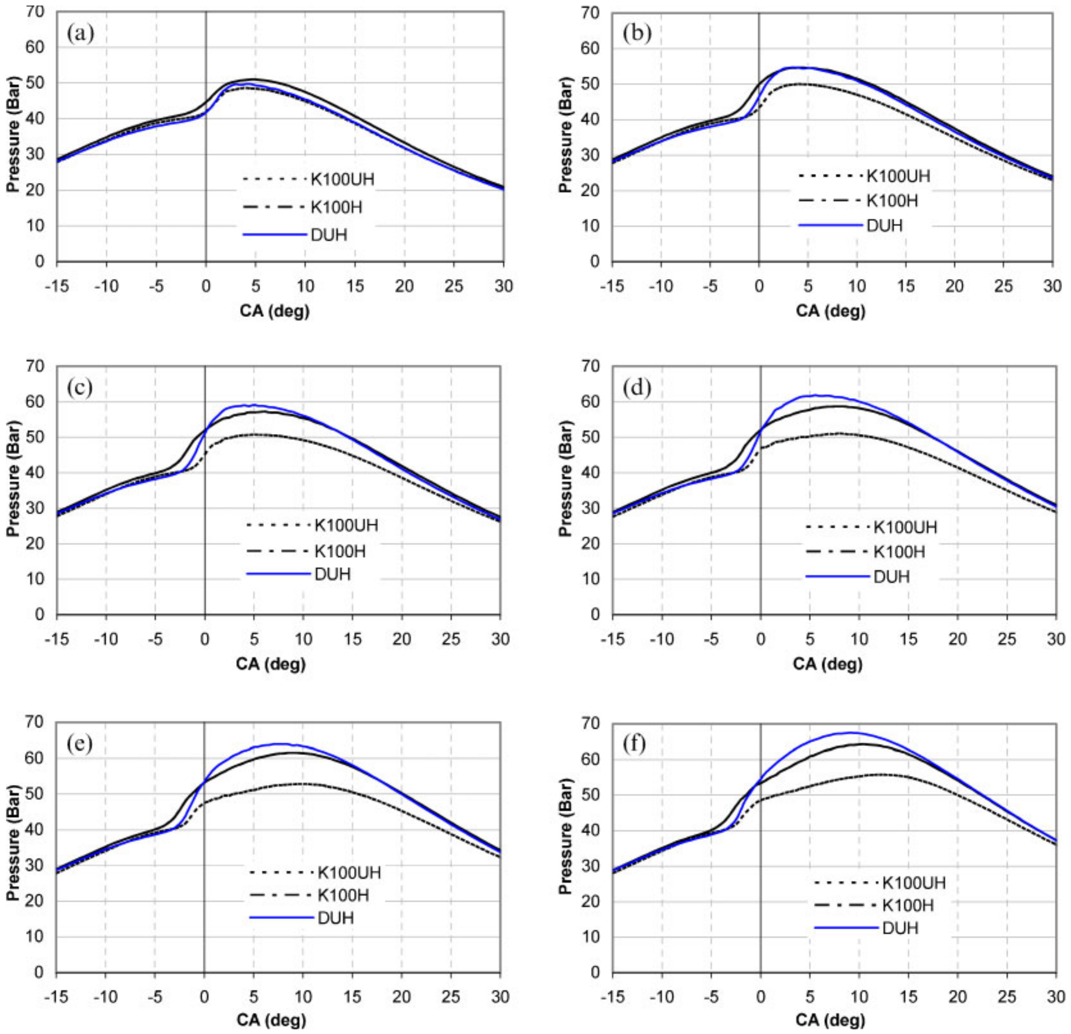


Fig. 10 Pressure–crank angle (CA) diagrams for various rated loads (K100UH, unheated Karanja oil; K100H, preheated Karanja oil; DUH, unheated diesel): (a) 0 per cent; (b) 20 per cent; (c) 40 per cent; (d) 60 per cent; (e) 80 per cent; (f) 100 per cent

the mineral diesel. Unheated Karanja oil always shows a lower peak pressure than mineral diesel. Heated Karanja oil shows a higher peak pressure at lower loads (Figs 10(a) and (b)) but lower peak pressure for higher loads in comparison with mineral diesel (Figs 10(c) to (f)). At all engine loads, combustion starts earlier for heated Karanja oil than mineral diesel while, for unheated Karanja oil, the start of combustion is delayed with respect to mineral diesel. Ignition delay for all fuels decreases as the engine load increases because the preheated fuel and gas temperature inside the cylinder is higher at high engine loads, thus it reduces the physical ignition delay.

The start of combustion reflects the variation in ignition delay because the fuel pump and injector settings were kept identical for all fuels. Combustion starts earlier for heated Karanja oil (Fig. 10) because of reduction in the viscosity at higher temperatures. Combustion starts later for unheated Karanja oil owing to the longer ignition delay.

Figure 11(a) shows the maximum cylinder pressure at different loads for different fuels. It shows that, at all engine loads, the peak pressure for diesel is higher than for Karanja oil. The peak pressure for heated Karanja oil is comparable with mineral diesel, but the peak pressure of unheated Karanja oil is significantly lower than mineral diesel. The peak pressure for mineral diesel is higher because of the shorter ignition delay and fast burning of accumulated fuel. Figure 11(b) shows the crank angle, at which the peak cylinder pressure is attained for all fuels at different engine operating conditions. It can be observed that, with increasing engine load, the

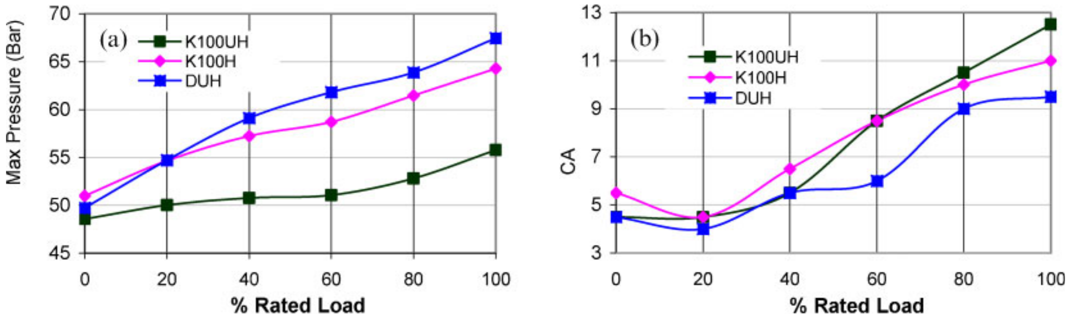


Fig. 11 (a) Maximum pressure and (b) crank angle (CA) at which the maximum pressure is obtained versus rated load (K100UH, unheated Karanja oil; K100H, preheated Karanja oil; DUH, unheated diesel)

peak cylinder pressure shifts away from the TDC (Fig. 11(b)).

Figure 12 shows the variation in the rate or pressure rise dP/dθ with crank angle at different loads for all three fuels. The maximum rate of pressure rise varies from 2.7 bar/deg at lower engine loads to 6.3 bar/deg at higher engine loads. The rate of pressure rise is higher for mineral diesel at all engine loads (Fig. 13(a)) because of the higher rate of heat release during premixed combustion (due to the higher volatility of mineral diesel). Figure 13(b) shows the crank angle at which the peak cylinder pressure rise rate is attained for all fuels at different engine operating conditions.

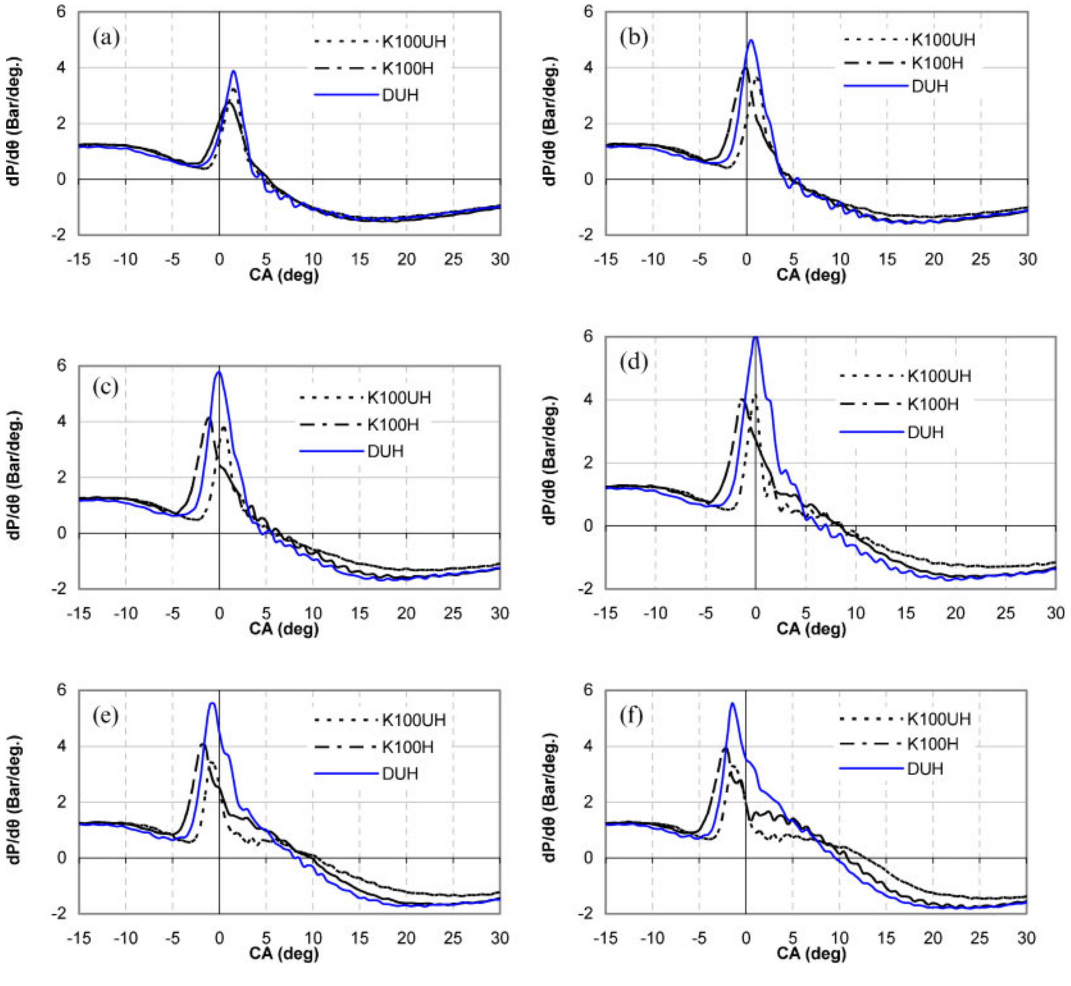


Fig. 12 Rate of pressure rise diagrams for various rated loads (K100UH, unheated Karanja oil; K100H, heated Karanja oil; DUH, unheated diesel; CA, crank angle): (a) 0 per cent; (b) 20 per cent; (c) 40 per cent; (d) 60 per cent; (e) 80 per cent; (f) 100 per cent

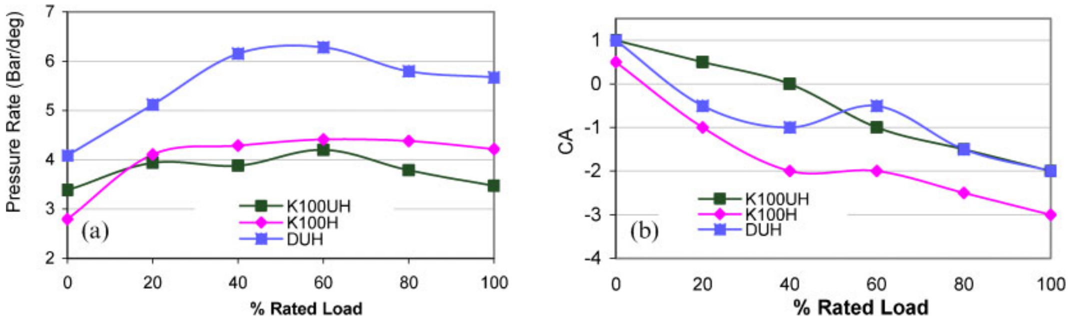


Fig. 13 (a) Maximum pressure rate and (b) crank angle (CA) at which the maximum pressure rate is obtained versus rated load (K100UH, unheated Karanja oil; K100H, preheated Karanja oil; DUH, unheated diesel)

3.2.2 *Instantaneous rate of heat release*

Figure 14 shows the heat release rate diagrams for heated and unheated Karanja oil with respect to mineral diesel at different engine operating conditions. Because of the vaporization of the fuel accumulated during ignition delay, initially a negative heat release is observed and, after combustion is initiated, the heat release becomes positive. This negative heat release is higher in the case of unheated Karanja oil because of the larger latent heat of vaporization required for evaporation of vegetable

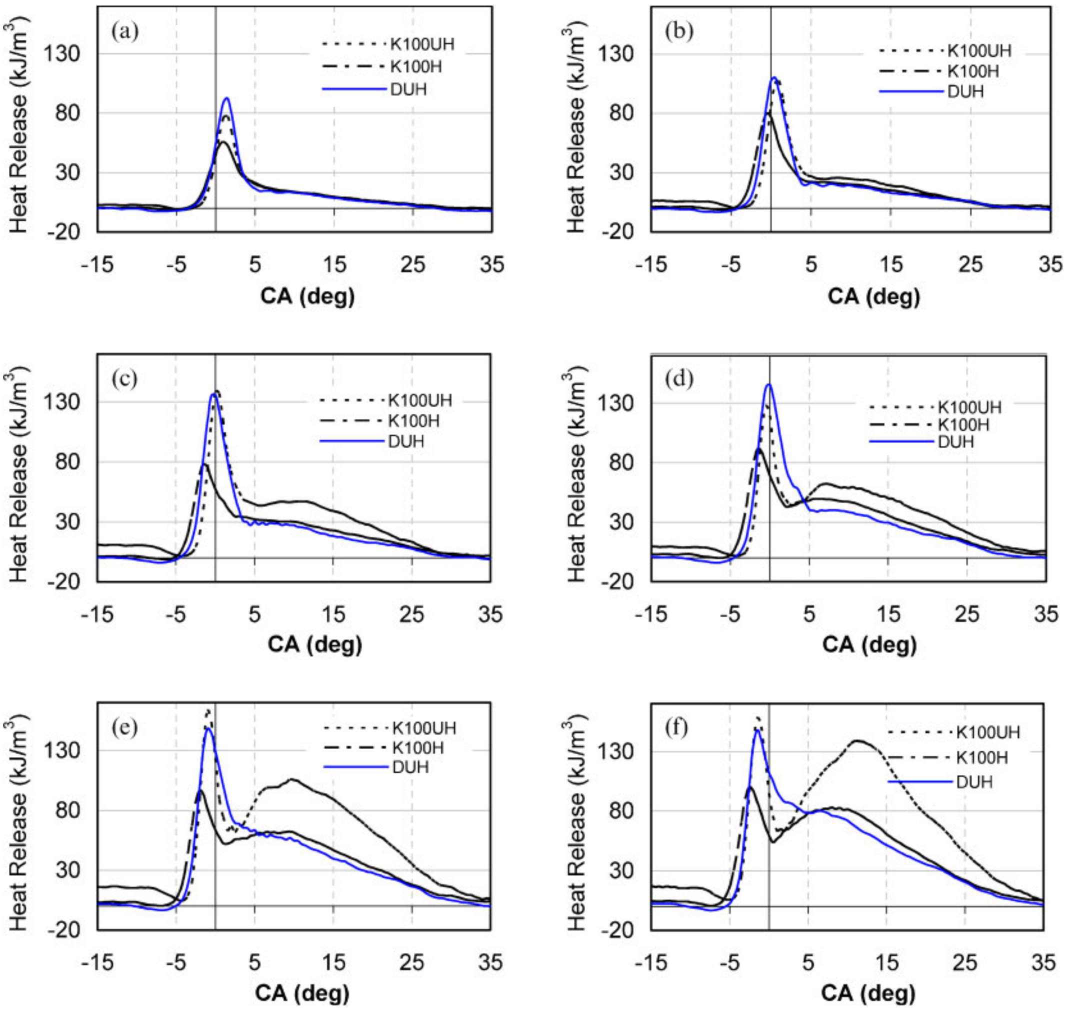


Fig. 14 Instantaneous heat release–crank angle (CA) diagrams for various rated loads (K100UH, unheated Karanja oil; K100H, preheated Karanja oil; DUH, unheated diesel): (a) idle; (b) 20 per cent; (c) 40 per cent; (d) 60 per cent; (e) 80 per cent; (f) 100 per cent

oils. Karanja oil shows identical combustion stages for lower loads as mineral diesel. After the ignition delay, the premixed fuel–air mixture burns rapidly. It can be observed that combustion starts earlier for heated Karanja oil under all engine operating conditions. The premixed combustion heat release is higher for mineral diesel at lower engine loads owing to the higher volatility and better mixing of mineral diesel with air. However, at higher engine loads, because of heating of the engine, unheated Karanja oil shows a higher premixed heat release. The lowest mixing controlled heat release from unheated Karanja oil may be due to polymerization of Karanja oil when it leaves the injector. For higher engine loads, late combustion is significant for unheated Karanja oil, because this polymerized oil burns more slowly.

3.2.3 *Cumulative heat release diagram*

Figure 15 shows the cumulative heat release for all fuels at different engine load conditions. These graphs show the tendency of earlier release of fuel energy for heated Karanja oil, which becomes more prominent at higher engine loads. The cumulative heat release curve of heated Karanja oil is almost similar to that of mineral diesel, but unheated Karanja oil shows quite a high cumulative heat release compared with mineral diesel, which con-

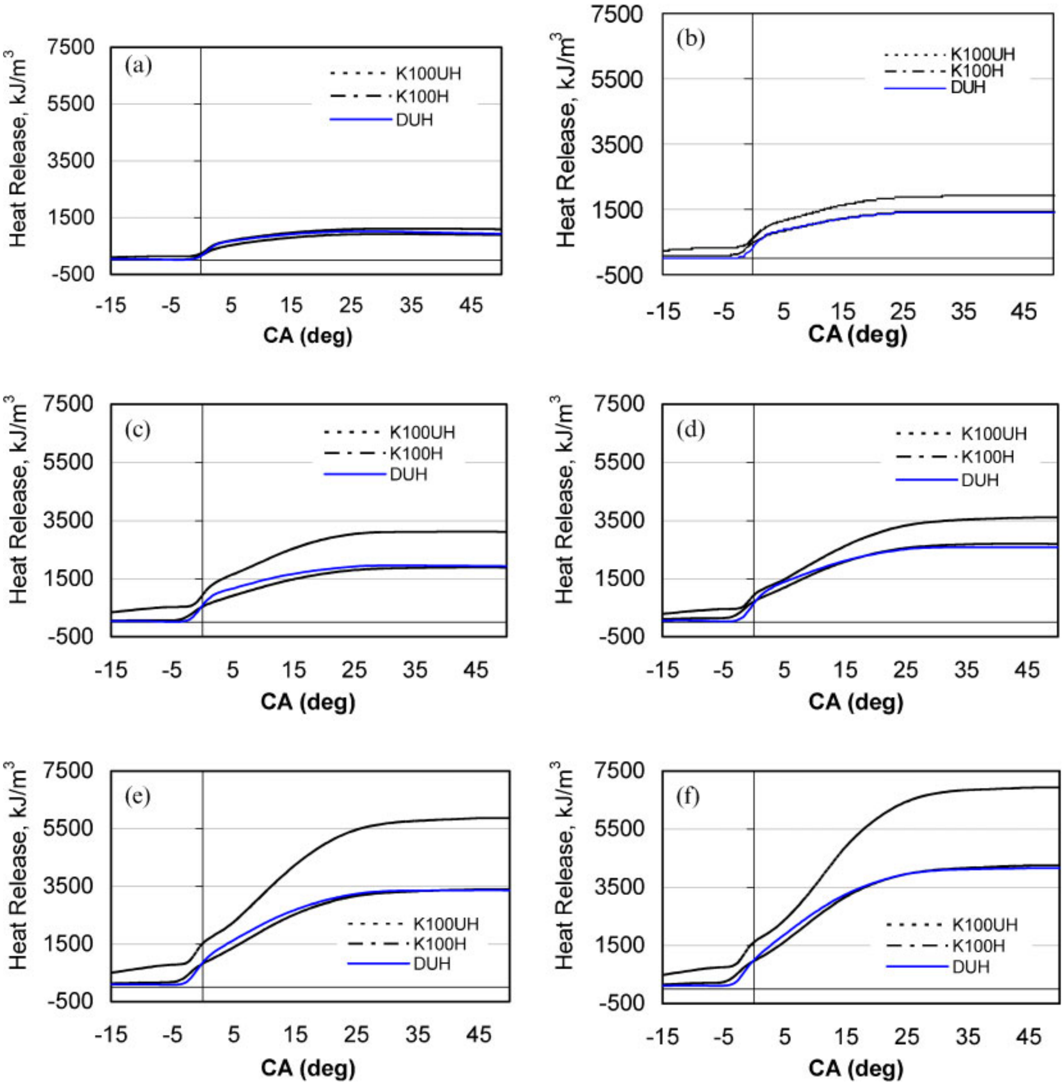
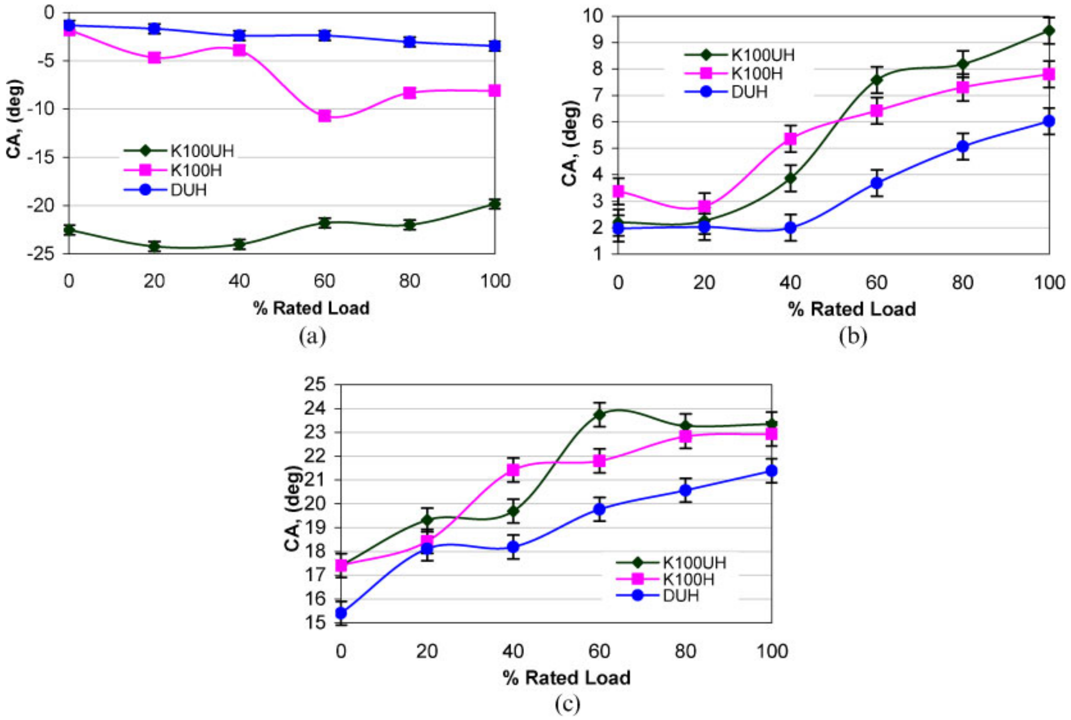


Fig. 15 Cumulative heat release–crank angle (CA) diagrams for various rated loads (K100UH, unheated Karanja oil; K100H, preheated Karanja oil; DUH, unheated diesel): (a) 0 per cent; (b) 20 per cent; (c) 40 per cent; (d) 60 per cent; (e) 80 per cent; (f) 100 per cent



(a) (b) (c)

Fig. 16 Crank angle (CA) for (a) 5 per cent mass faction burned, (b) 50 per cent mass faction burned, and (c) 90 per cent mass faction burned

firms the poor fuel energy utilization in the case of this fuel in the unmodified diesel engine. The heating of the Karanja oil however, brings its combustion behaviour very close to mineral diesel.

3.2.4 *Crank angle for the mass fraction burned*

Figure 16(a) shows the crank angle for 5 per cent mass fraction burned. This figure shows that 5 per cent fuel burns earlier for unheated Karanja oil. This is due to the earlier start of combustion for Karanja oil, as suggested earlier. Heated Karanja oil shows a delayed start of combustion with respect to unheated Karanja oil which indicated the formation of less volatile heavier molecules because of preheating of the oil. Figure 16(b) shows the crank angle for 50 per cent mass fraction burned at different engine load conditions. Viscous Karanja oil takes more time for 50 per cent combustion than mineral diesel does. Figure 16(c) shows the crank angle for 90 per cent mass fraction burned at different engine load conditions. This is similar to the 50 per cent mass fraction burned graph. More fuel is required in the case of Karanja oil because the calorific value of these fuels is lower than mineral diesel. These factors lead to longer combustion duration for Karanja oil.

3.2.5 *Combustion duration*

Figure 17 shows the variation in combustion duration for different fuels at different engine loads. The combustion duration for unheated Karanja oil is quite high compared with mineral diesel at all engine operating conditions. This is possibly due to the slower rate of combustion of Karanja oil. For heated Karanja oil, the combustion duration is comparable with mineral diesel.

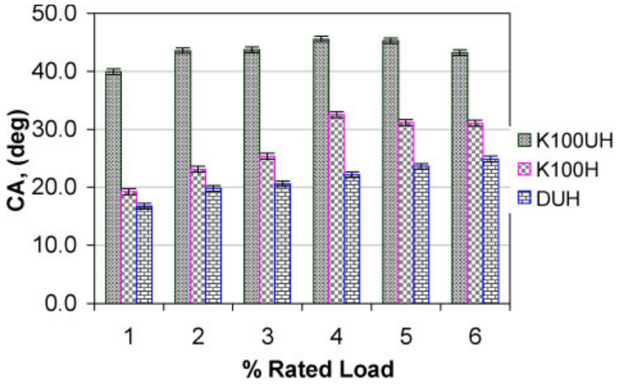


Fig. 17 Combustion duration (crank angle) at various rated loads for three different fuels (K100UH, unheated Karanja oil; K100H, preheated Karanja oil; DUH, unheated diesel)

4 CONCLUSION

The performance, emissions, and combustion tests were conducted with mineral diesel, heated Karanja oil, and unheated Karanja oil at different loads at a constant engine speed (1500 r/min). From the experimental results obtained, preheated Karanja oil is found to be a suitable alternative fuel for CI engines. Karanja oil can be preheated by utilizing the waste heat of exhaust gases and this preheating significantly improves the performance and emission characteristics of Karanja oil. The BSFC and exhaust gas temperatures for preheated Karanja oil were found to be higher than mineral diesel. The thermal efficiency was slightly lower for preheated Karanja oil than mineral diesel. The CO_2, CO, HC, and NO emissions were lower for preheated Karanja oil than mineral diesel.

A direct-injection stationary diesel engine was operated under a steady state, at different engine loads at 1500 r/min to investigate the combustion characteristics of preheated and unheated Karanja oil with respect to mineral diesel. Experiments show that the combustion phases are almost similar for preheated Karanja oil and mineral diesel. Preheated Karanja oil shows lower combustion delay but slower heat release rate. The combustion durations for both preheated and unheated Karanja oils are longer than mineral diesel but preheating the Karanja oil brings the combustion duration quite close to mineral diesel. The highest maximum in-cylinder pressure was observed for mineral diesel for higher load conditions, but, at lower loads, a higher peak cylinder pressure was obtained with preheated Karanja oil. Detailed combustion analysis suggests that preheated Karanja oil shows identical combustion behaviour similar to mineral diesel. Hence, the waste heat of exhaust gas can be effectively utilized to preheat the Karanja oil in order to improve its combustion properties as a diesel engine fuel.

REFERENCES

1 **Bajpai, S., Sahoo, P. K.,** and **Das, L. M.** Feasibility of blending karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine. *Fuel*, 2009, **88**(4), 705–711.

2 **Agarwal, A. K.** Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Prog. Energy Combust. Sci.*, 2007, **33**(3), 233–271.

3 **Kureel, R. S., Singh, C. B., Gupta, A. K.,** and **Pandey, A.** *Karanja: a potential source of biodiesel*, 2008 (National Oilseeds and Vegetable Oil Development Board, Ministry of Agriculture, Government of India, Gurgaon).

4 **Agarwal, D.** and **Agarwal, A. K.** Performance and emissions characteristics of Jatropha oil (preheated and blends) in a direct injection compression ignition engine. *Appl. Thermal Engng*, 2007, **27**(13), 2314–2323.

5 **Ghassan, M. T., Mohamad, I. A.,** and **Aiman, M. A.** Factorial analysis of diesel engine performance using different types of biofuels. *J. Environ. Managmt*, 2007, **84**(4), 401–411.

6 **Ramadhas, A. S., Jayaraj, S.,** and **Muraleedharan, C.** Characterization and effect of using rubber seed oil as fuel in the compression ignition engines. *Renewable Energy*, 2005, **30**, 795–803.

7 **Forson, F. K., Oduro, E. K.,** and **Donkoh, E. H.** Performance of Jatropha oil blends in a diesel engine. *Renewable Energy*, 2004, **29**, 1135–1145.

8 **Kumar, M. S., Ramesh, A.,** and **Nagalingam, B.** An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine. *Biomass Bioenergy*, 2003, **25**, 309–318.

9 **Rakopoulos, C. D., Antonopoulos, K. A., Rakopoulos, D. C., Hountalas, D. T.,** and **Giakoumis, E. G.** Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or biodiesels of various origins. *Energy Conversion Managmt*, 2006, **47**(18–19), 3272–3287.

10 **He, Y.** and **Bao, Y. D.** Study on rapeseed oil as alternative fuel for a single cylinder diesel engine. *Renewable Energy*, 2003, **28**, 1447–1453.

11 **Almeida, S. C. A. D., Belchior, C. R., Nascimento, M. V. G., Vieira, L. D. S. R.,** and **Fleury, G.** Performance of a diesel generator fuelled with palm oil. *Fuel*, 2002, **81**, 2097–2102.

12 **Ramadhas, A. S., Jayaraj, S.,** and **Muraleedharan, C.** Use of vegetable oils as I.C. engine fuels – a review. *Renewable Energy*, 2004, **29**, 727–742.

13 **Hemmerlein, N., Korte, V.,** and **Richter, H.** Performance, exhaust emission and durability of modern diesel engines running on rapeseed oil. SAE paper 910848, 1991.

14 **Yu, C. W., Bari, S.,** and **Ameen, A.** A comparison of combustion characteristics of waste cooking oil with diesel as fuel in a direct injection diesel engine. *Proc. IMechE, Part D: J. Automobile Engineering*, 2002, **216**(3), 237–243. DOI: 10.1243/0954407021529066.

15 **Hebbal, O. D., Reddy, K. V.,** and **Rajagopal, K.** Performance characteristics of a diesel engine with Deccan Hemp oil. *Fuel*, 2006, **85**(14–15), 2187–2194.

16 **Huzayyin, A. S., Bawady, A. H., Rady, M. A.,** and **Dawood, A.** Experimental evaluation of diesel engine performance and emission using blends of Jojoba oil and diesel fuel. *Energy Conversion Managmt*, 2004, **45**(13–14), 2093–2112.

17 **Gangwar, H. K.** and **Agarwal, A. K.** Combustion characteristics of Jatropha oil blends in a transportation engine. SAE paper 2008-01-1383, 2008.

18 **Agarwal, A. K.** and **Rajamanoharan, K.** Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. *Appl. Energy*, 2009, **86**(1), 106–112.

19 **Banapurmath, N. R., Tewari, P. G.,** and **Hosmath, R. S.** Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methyl esters. *Renewable Energy*, 2008, **33**(9), 1982–1988.

20 **Nwafor, O. M. I.** Emission characteristics of diesel engine running on vegetable oil with elevated fuel inlet temperature. *Biomass Bioenergy*, 2004, **27**, 507–511.

21 **Bari, S., Lim, T. H.,** and **Yu, C. W.** Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. *Renewable Energy*, 2002, **27**, 339–351.

22 **Nwafor, O. M. I.** The effect of elevated fuel inlet temperature on performance of diesel engine running on neat vegetable oil at constant speed conditions. *Renewable Energy*, 2003, **28**, 171–181.

23 **Mahanta, P., Mishra, S. C.,** and **Kushwah, Y. S.** An experimental study of *Pongamia pinnata* L. oil as a diesel substitute. *Proc. IMechE, Part A: J. Power Energy*, 2006, **220**(7), 803–808. DOI: 10.1243/09576509JPE172.