Effect of Karanja biodiesel blends on particulate emissions from a transportation engine

Article in Fuel · February 2015

DOI: 10.1016/j.fuel.2014.09.124

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Fuel 141 (2015) 154–163

Contents lists available at ScienceDirect

Fuel

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

Effect of Karanja biodiesel blends on particulate emissions from a transportation engine

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HIGHLIGHTS

- Effect of biodiesel and blends on particulate size-number distribution.
- Peak numbers concentration increased with increasing engine speed.
- Total number concentration was lowest for 10% biodiesel blend.
- Upto B20 reduced particulate number emissions.

ARTICLE INFO

Article history:
Received 30 October 2013
Received in revised form 25 August 2014
Accepted 23 September 2014
Available online 18 October 2014

Keywords:
Biodiesel
Karanja
Particulate
Size-number distribution
Particulate number emissions

ABSTRACT

Recent emission control legislations restrict the particulate mass emissions as well as particle numbers due to severe adverse health effects of smaller size particulates. Therefore from health perspective, reduction in particulate mass as well as numbers, both are desired from any potential alternative fuel. In this experimental investigation, effect of Karanja biodiesel and its blends on particulate size-number distribution, size-surface area distribution and total particulate number concentration at various engine operating conditions was experimentally studied using a direct injection compression ignition engine. It was observed that peak number concentration of particulates increased with increasing engine speed for all test fuels. Total particulate number concentration was highest for KOME100 and lowest for KOME10, amongst all test fuels. Smaller concentration of Karanja biodiesel (upto 20%) was effective in reducing the particulate number emissions.

1. Introduction

Transportation sector accounted for 27% of total world's delivered energy consumption in 2008, and World's total energy consumption for transport sector is expected to reach 3349.3 million tonnes of oil equivalent (MTOE) in 2035 in comparison to 2314.6 MTOE in 2008 [1]. In the present scenario, liquid fuels account for 95% of the total transportation fuel mix and in the absence of significant technological advances, this trend is predicted to continue till 2035 [1]. Biodiesel is getting global consideration as a promising renewable alternative to the mineral diesel. Emission characteristics of biodiesel fuelled engine changes due to differences in chemical and physical properties of biodiesel and mineral diesel [2–5].

Major pollutants of concern emanating from CI engines are oxides of nitrogen (NOx) and particulate matter (PM). The problem is complicated by PM-NOx trade-off and ever shrinking limits on these pollutants imposed by newer emission legislations. In newer emission legislations being adopted globally, regulating particulate numbers is gaining momentum because their adverse health effects are directly related to the smaller size respirable particulates, which do not contribute significantly towards particulate mass. From health perspective, reduction in particulate mass as well as numbers, both are important. Kittelson et al. reported that quite often, reduction in particulate mass is associated with increase in number of smaller size particles, which enhances the toxic potential of the engine exhaust [6]. Smaller soot particles are more likely to remain suspended in the atmospheric air for longer time; therefore they have higher likelihood of penetration into the bronchi and alveolar regions of the lungs, once inhaled. These smaller particles tend to be more reactive due to their larger surface to volume ratio [7,8]. Hence it is important to investigate the effect of biodiesel on particulate size-number distribution in full range of engine operating conditions for a typical transportation engine used in a sport utility vehicle (SUV). Kawano et al. reported that an increase in engine load increases the peak number concentration in case of diesel and reduces the peak concentration

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http://dx.doi.org/10.1016/j.fuel.2014.09.124
0016-2361/

Table 1
Technical specifications of the test engine.

Engine type	Four stroke in-line, Naturally-aspirated, Water-cooled direct injection compression ignition engine
No. of cylinders	Four
Compression ratio	18:1
Combustion system	Direct injection, re-entrant bowl
Bore/ stroke	88.9/101.6 mm
Swept volume	2520 cc
Fuel injection timing	(SOI) 17 ± 1° BTDC
Rated power	41 kW/3000 rpm
Max. torque	152 Nm/1800 rpm

for rapeseed methyl ester fuelled operation [9]. Zhu et al. reported increase in particulate number concentration with increasing biodiesel concentration with respect to mineral diesel [10]. Agarwal et al. reported increase in particle number concentration at lower loads and reduction at higher loads for B20 in comparison to mineral diesel [7].

In different parts of the world, depending upon climatic and agricultural conditions, different feedstocks are chosen for biodiesel production. Jatropha and Karanja are most widely accepted [11–14] feedstocks for biodiesel production in South Asia because biofuel policy of the Government of India discourages utilization of prime agricultural land for biofuel production. Among these two, Jatropha got prime attention in the last decade due to its shorter gestation period. However per hectare oil production from Jatropha plantation has not met the expectations. In this scenario, Karanja, which is a tree-borne feedstock for biodiesel production and is well adapted to local climatic conditions, is more suitable for long-term sustainable biodiesel production in this region. Detailed particulate size-number distribution characterization of Karanja biodiesel and its blends in transportation engine is not investigated extensively. In this experimental research, effect of Karanja biodiesel and its blends on particulate size-number distribution characteristics were compared with baseline mineral diesel at different engine speeds and loads, in order to find out appropriate blending limit of Karanja biodiesel in transportation engines, which results in reduction of particulate numbers.

2. Experimental setup

Effect of Karanja biodiesel and its blends on particulate size-number distribution at different engine speeds and loads were investigated in a transportation direct injection compression ignition (DICI) sports utility vehicle (SUV) engine. Detailed technical specifications of the test engine used in the experiments are given in Table 1. 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). Fig. 1 shows the schematic of the experimental setup. This test engine (Mahindra & Mahindra, India; MDI 3000) was coupled to an eddy-current dynamometer (Schenck-Avery, India; ASE-70) for controlling the engine speed and load. Size-number distribution of particulate emissions in the engine exhaust was characterized by Engine Exhaust Particle Sizer™ (EEPS) spectrometer (TSI Inc., USA; 3090). EEPS provides both high temporal and reasonable size resolution by using the same basic technique as that of scanning mobility particle sizer (SMPS) but with multiple detectors working in parallel [15]. EEPS is designed specifically to dynamically measures particulates emitted from engines and vehicles. It measures particle size ranging from 5.6 to 560 nm with a size resolution of 16 channels per decade (a total of 32 channels) upto a maximum concentration of 10^8 particles/cm^3 in the engine exhaust. Number concentration of particles in the engine out exhaust was higher than the maximum measuring range of EEPS, hence the exhaust gas was diluted 560 times before entry into the EEPS using a rotating disk thermo-diluter (Matter Engineering, UK; MD19-2E). Number concentration of the particulates was measured in the diluted exhaust and concentration in the

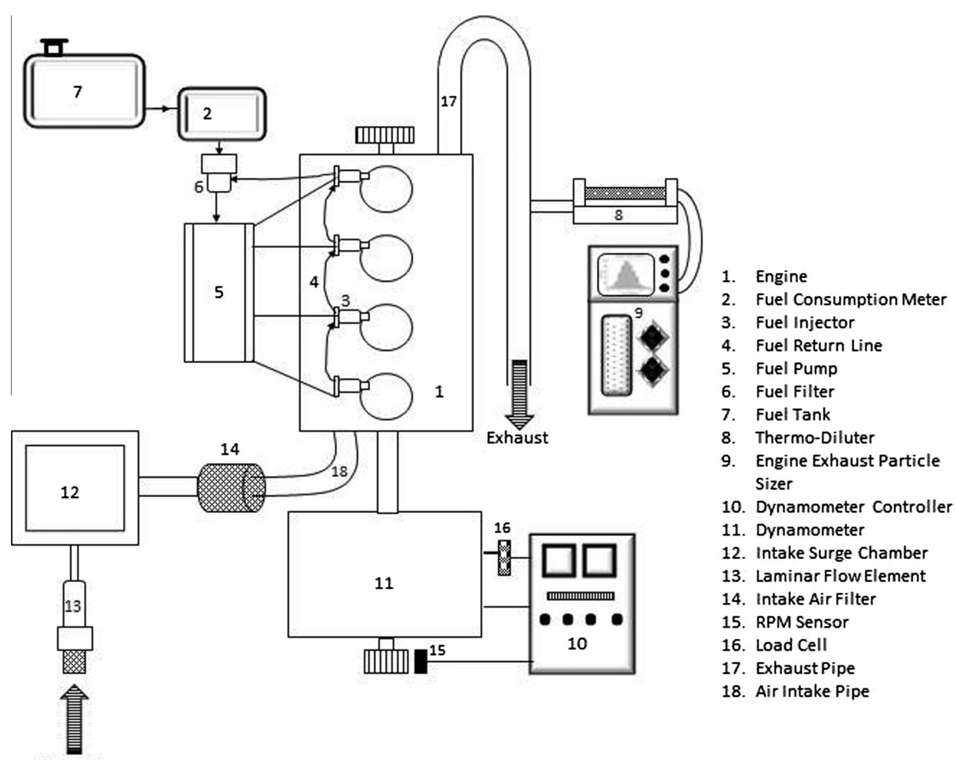

Fig. 1. Schematic of the experimental setup.

Table 2
Properties of the test fuels.

Test fuel	Viscosity @ 40 °C (cSt)	Density (g/cm^3)	Calorific value (MJ/kg)
Diesel	2.78	0.831	43.79
KOME05	2.91	0.833	43.48
KOME10	3.04	0.836	43.18
KOME20	3.11	0.841	42.57
KOME50	3.51	0.856	40.8
KOME100	4.42	0.881	37.98

engine-out exhaust was calculated by multiplying the measured values with the dilution factor. Particulate samples were analyzed once every second for one minute duration i.e. 60 readings were taken in 1 min sampling duration. Particulates enter the instrument through a cyclone with a 1 μm cut-off. This removes larger particles (>1 μm) that are above the instrument's measuring capabilities. The particle laden gas then passes through an electrical diffusion charger, where ions are generated. These ions mix with the particles and provide a predictable charge based on the particle size. The charged particles then enter into an annular space

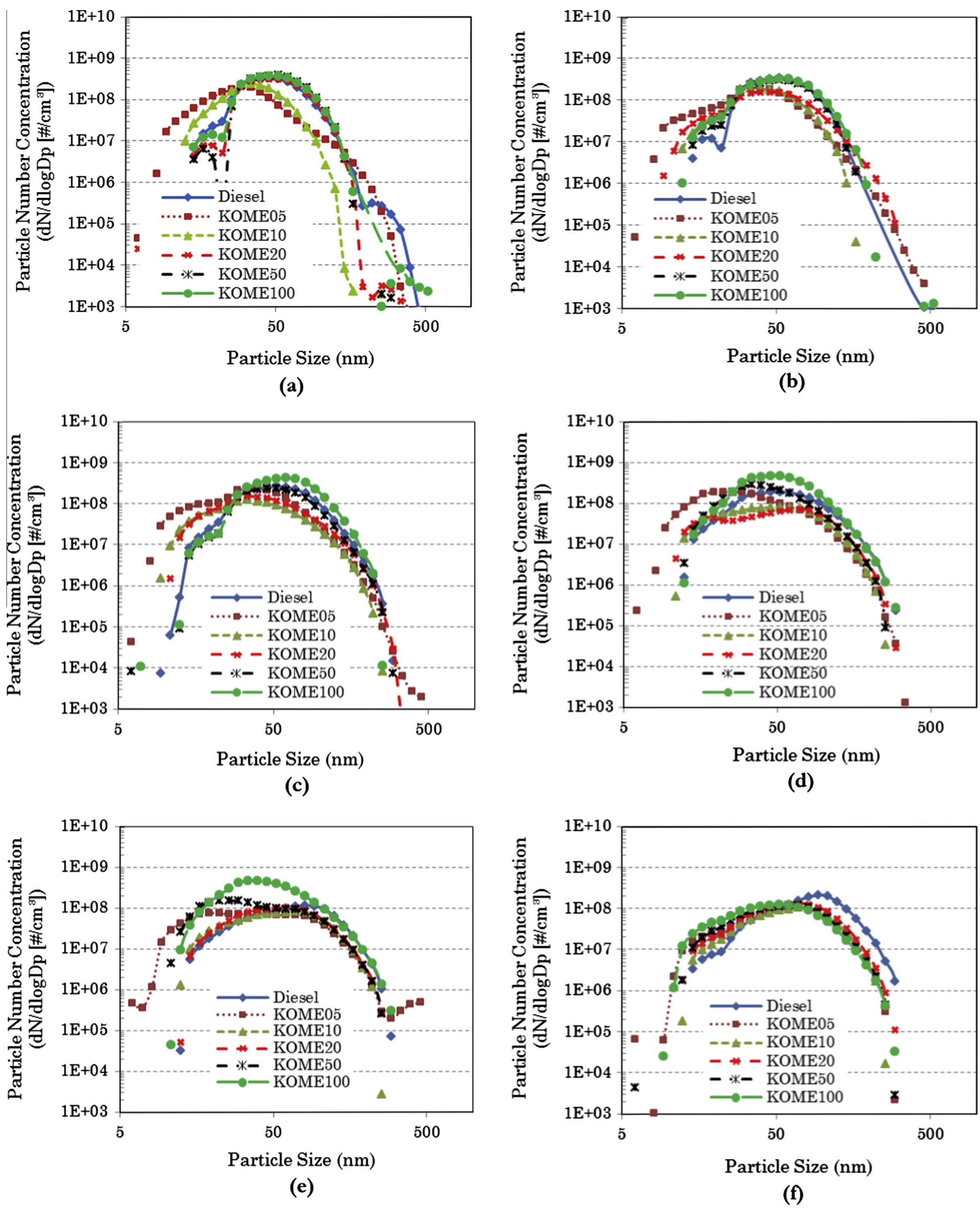

Fig. 2. Variation of particulate size-number distribution at BMEP of (a) 0.2 bar, (b) 1.4 bar, (c) 2.8 bar, (d) 4.2 bar, (e) 5.6 bar and (f) 6.8 bar at1800 rpm.

between two cylinders, which is filled with clean sheath air. The particles pass by a central rod, which has a high voltage to produce an electric field, which repels the particulate outwards (towards the electrometer rings). The particles are then collected on electrometer rings, thus transferring their charge to a sensitive electrometer of each ring depending on their size [15]. Detailed description of experimental setup and conditions is provided in an earlier publication [16].

In the present investigation, particle size-number distribution of 5%, 10%, 20%, 50% Karanja biodiesel blends and 100% biodiesel vis-à-vis baseline mineral diesel were experimentally evaluated at varying engine speeds and loads. Important physical and chemical properties of Karanja biodiesel and its blends are shown in Table 2. Steady state measurement of particulate size-number distribution was performed after engine stabilization at fixed engine speeds and loads.

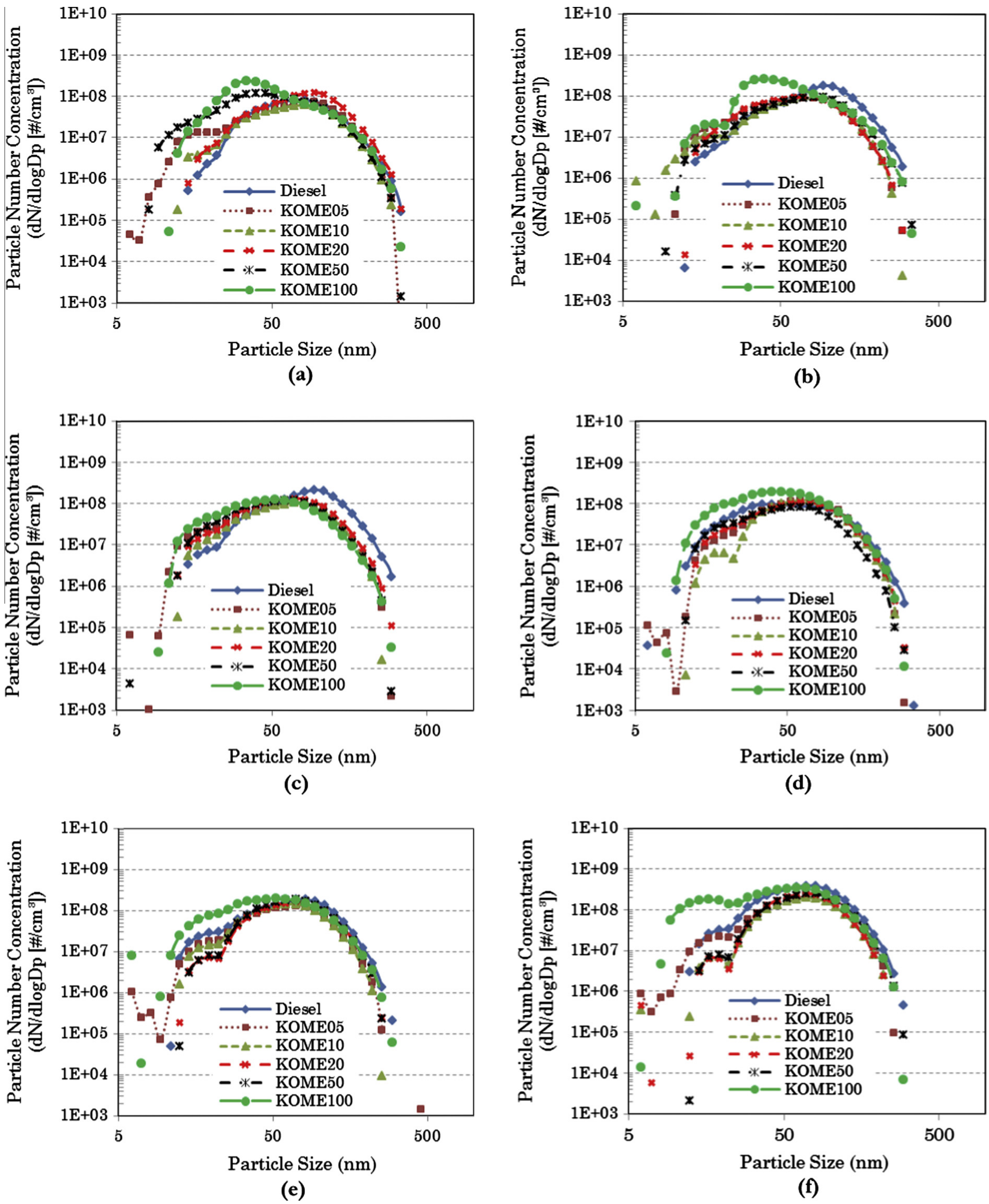

Fig. 3. Variation of particulate size-number distribution at 6.8 bar BMEP at (a) 1200 rpm, (b) 1500 rpm, (c) 1800 rpm, (d) 2100 rpm, (e) 2400 rpm and (f) 2600 rpm.

3. Results and discussion

Particulate size-number distribution was measured using EEPS in the size range of 5.6–560 nm for different biodiesel blends and mineral diesel. Fig. 2 shows the variation of particulate number concentration for different Karanja biodiesel blends with varying engine load at rated speed of 1800 rpm. The results are presented on log-normal scale. Particulate size measuring range (5.6–560 nm) of EEPS is evenly divided in 32 divisions on logarithmic scale to ensure sufficient resolution for smaller size as well as larger size particles. Due to logarithmic division of particle size diameters, *Y*-axis scale of number concentration is normalized by multiplying with [dN/dlogDp] so that area under these curves represents total particle number. KOME05 shows lowest number concentration of particulates at lower engine loads. Concentration of smaller nuclei mode particulates (<20 nm) is highest for KOME05 at 0.2–5.6 bar brake mean effective pressure (BMEP). However at 6.8 bar BMEP, KOME100 gives higher number concentration of nuclei mode particles. Number concentration of accumulation mode particles was lower for lower biodiesel concentration blends

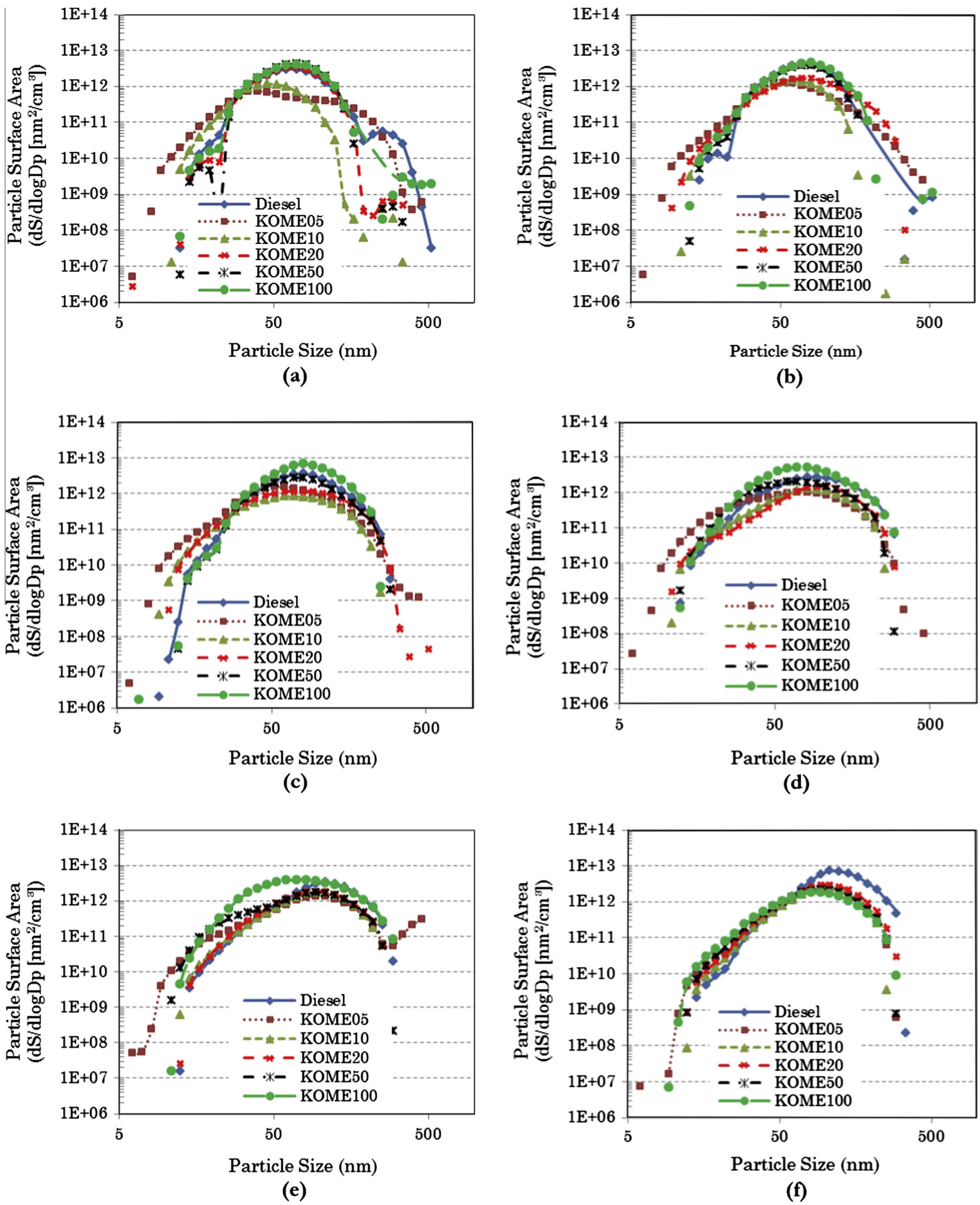

Fig. 4. Variation of particulate size-surface area distribution at 1800 rpm for BMEP of (a) 0.2 bar, (b) 1.4 bar, (c) 2.8 bar, (d) 4.2 bar, (e) 5.6 bar and (f) 6.8 bar.

(KOME05 and KOME10) at all engine loads (BMEP). Peak number concentration of particulates is highest for KOME100 from 1.4 to 5.6 bar BMEP. Agarwal et al. also reported highest peak number concentration for B100 for 20–100% engine load [7]. At rated engine load, mineral diesel emits highest number density of larger particulate, however concentration of smaller diameter particles is higher for Karanja biodiesel blends. Similar trend was also reported at 100% engine load in other investigations, where mineral diesel showed peak concentrations for biggest particles among the three tested fuels namely B100, B20 and mineral diesel [7]. It was observed that with increasing engine load, number concentration of particulates increased for all test fuels. At higher engine loads, higher fuel quantity is injected and more fuel is combusted in diffusion combustion mode, hence more number of particles are formed [17]. Lower soot oxidation takes place in the expansion stroke because there is very little time available at the end of diffusion combustion, which leads to increase in particle number concentration at higher BMEPs [18]. With increasing engine load, concentration of larger size particles increased for all fuels. At higher engine loads, combustion takes place with lower excess oxygen but at higher cylinder pressure and temperature, therefore it contributes to higher soot nucleation and promotes the growth of existing soot nuclei [19]. With an increase in particle numbers, coagulation rate also increases. Hence larger particles are formed,

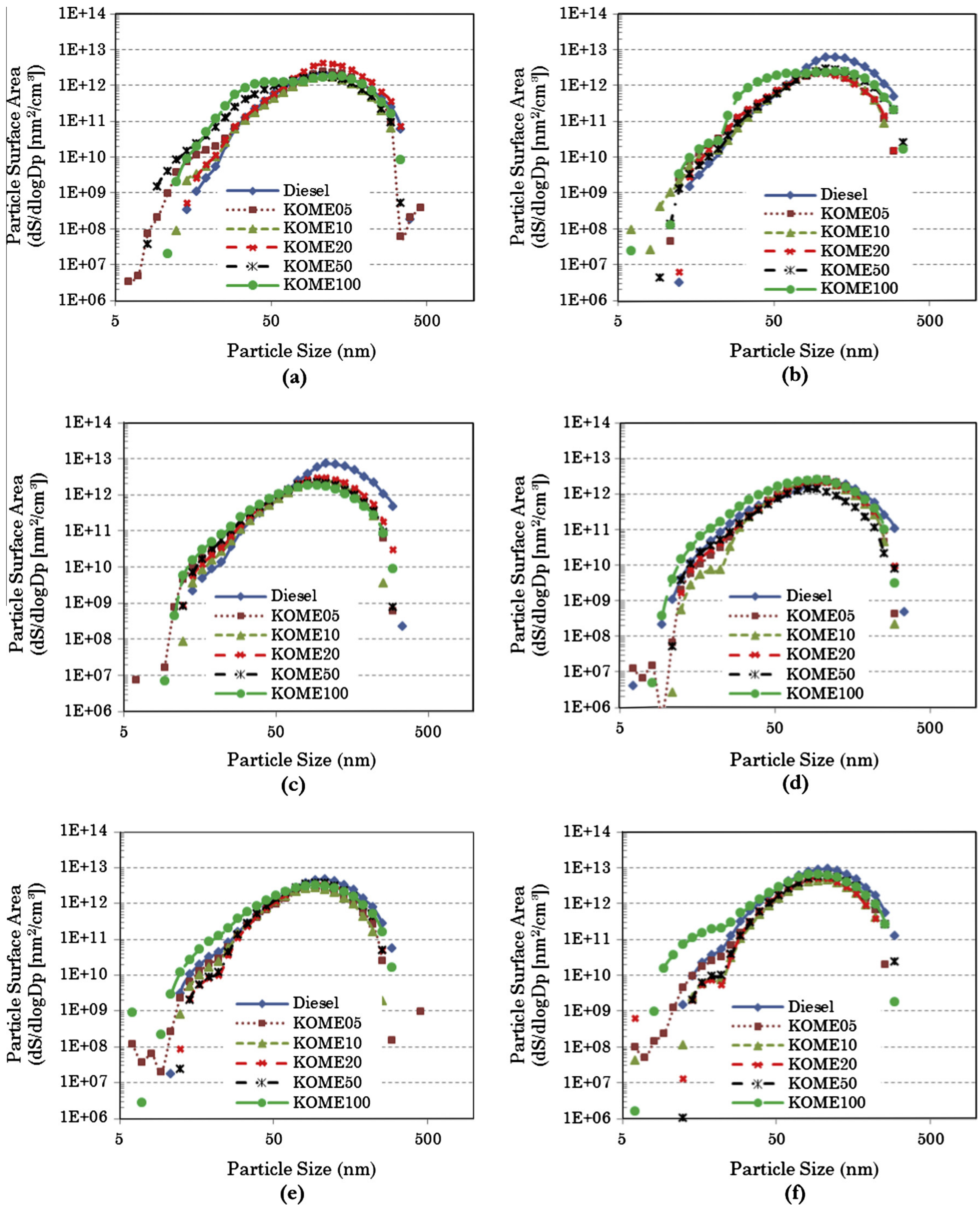

Fig. 5. Variation of particulate size-surface area distribution at 6.8 bar BMEP for engine speed of (a) 1200 rpm, (b) 1500 rpm, (c) 1800 rpm, (d) 2100 rpm, (e) 2400 rpm, and (f) 2600 rpm.

leading to an increase in the concentration of larger accumulation mode particles [17,20]. Fig. 2 indicates that the concentration of larger accumulation mode particulates is lower for higher biodiesel blends.

Fig. 3 shows the variation of particle size-number distribution for Karanja biodiesel blends with varying engine speed at full load condition. It is evident from the figure that peak number concentration of particles increases with increasing engine speed for all test fuels. As engine speed increases, time available for the combustion (in ms) reduces, which also reduces the time available for the re-burning/oxidation of soot already formed [21]. Shortening of time available for particulate oxidation increases concentration of particulates with increasing engine speed at full load condition. At full engine load for all engine speeds, concentration of smaller particulates is higher for higher biodiesel blends, while concentration of larger diameter particulates is higher for mineral diesel. Higher rate of oxidation of biodiesel soot particulates in comparison to mineral diesel is seen due to surface oxygen functionality of fuel bound oxygen in biodiesel, which may be responsible for reduction in particle size distribution [22].

Fig. 4 shows the variation of particulate surface area-size distribution for different Karanja biodiesel blends with varying engine load at 1800 rpm engine speed. Particulate surface area-size distribution has a direct bearing on the toxic potential of particulates because it is a measure of active sites available for adsorption of volatile hydrocarbon fractions and PAHs, which are extremely harmful and toxic for human health [7]. Particulate surface area-size distribution is also an indicator of effectiveness of the interaction of particulates with respiratory system of living beings, which in-turn determines their effect on the human health. Particulate surface area-size distribution of larger particulates in the engine exhaust increases with increasing engine load because the particulate number concentration in this size range increases.

Fig. 5 shows the variation of particle size-surface area distribution for Karanja biodiesel blends with varying engine speed at full load. Variation of particulate size-surface area distribution with

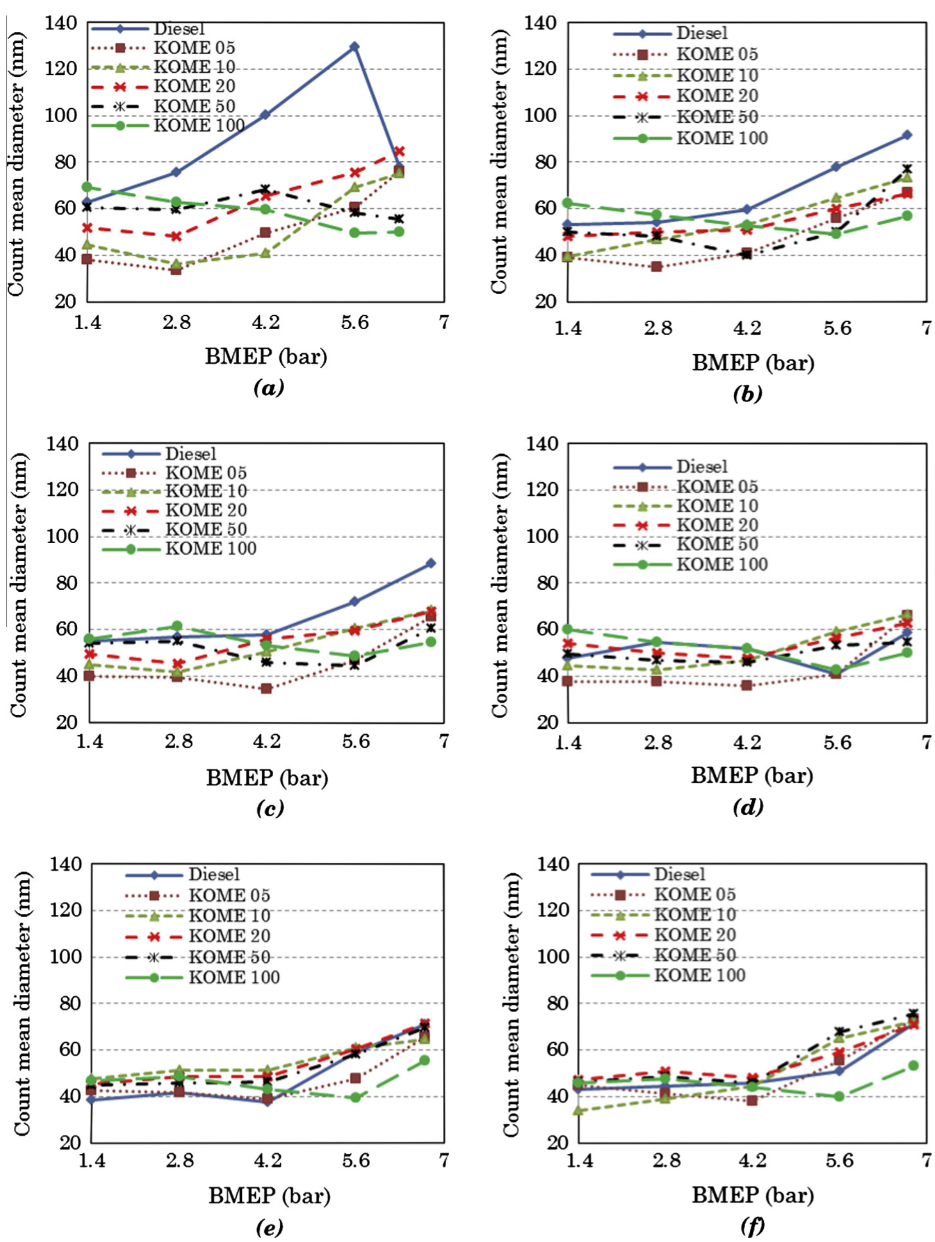

Fig. 6. Variation of particulate count mean diameter for Karanja biodiesel and blends vis-à-vis mineral diesel at (a) 1200, (b) 1500, (c) 1800, (d) 2100, (e) 2400 and (f) 2600 rpm engine speed.

engine speed at full load follows the trend of size-number distribution for all test fuels. Higher surface area of higher biodiesel blends for smaller particulates is an indicator of possibly higher toxic potential of particulates from these test fuels, although their exhaust appears cleaner visually in an unmodified engine. For using higher biodiesel blends, fuel injection system needs to be modified for reducing emissions of smaller particulates.

Fig. 6 shows the variation of particulate count mean diameter (CMD) for Karanja biodiesel blends with varying engine load and speed. CMD represents the number weighted arithmetic average of particulate size, which provides a basis for comparing average size of particulates at different operating conditions. At 1200 rpm and 5.6 bar BMEP, particulate CMD for diesel was higher than Karanja biodiesel blends because concentration of larger size particulates was higher and smaller diameter particulates were lower in number for mineral diesel in comparison to biodiesel. At 1200 rpm, differences in the CMD of mineral diesel and biodiesel blends were large, which reduced with increasing engine speed at all BMEPs. At 1200 rpm, with increase in engine load from 5.6 bar to 6.4 bar BMEP, reduction in CMD was observed for mineral diesel. It shows that rise in cylinder temperature with increasing engine speed facilitates oxidation of particulate, which reduces the CMD as well as total number concentration. This effect is significant at lower engine speeds, which is because of longer time available for oxidation reactions to take place at lower engine speeds. Kim et al. also reported a significant shift in particulate sizes towards smaller diameters, when using biodiesel at 2000 rpm in comparison to result of 1000 rpm [21]. This may be explained by the fact that the oxygen content in biodiesel plays a significant role at the lower engine speeds. In these conditions, available time for oxidation of particulates is enough. At full load (6.4 bar BMEP), CMD of 100% biodiesel was lowest among all test fuels at all engine speeds. Lapuerta et al. also reported smallest CMD for B100 at 1850 rpm engine speed and 6.34 bar BMEP [8]. CMD of B20 and B70 were lower than mineral diesel but higher than B100 at all reported operating modes [8]. Zhu et al. also reported smaller CMD for B100 in comparison to mineral diesel [20]. At higher engine load, relatively higher increase in nuclei

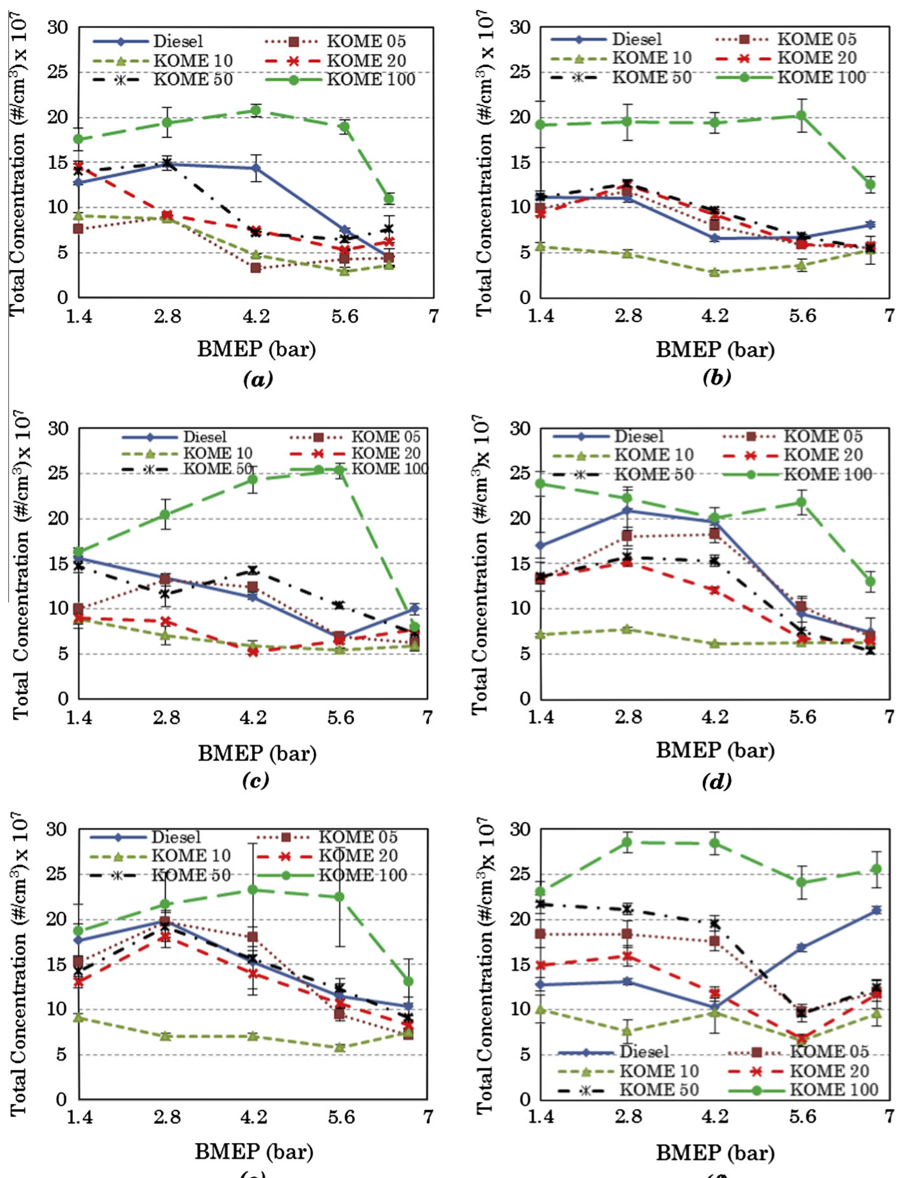

Fig. 7. Variation of particulate total number concentration of Karanja biodiesel and blends vis-à-vis mineral diesel at (a) 1200, (b) 1500, (c) 1800, (d) 2100, (e) 2400 and (f) 2600 rpm engine speed.

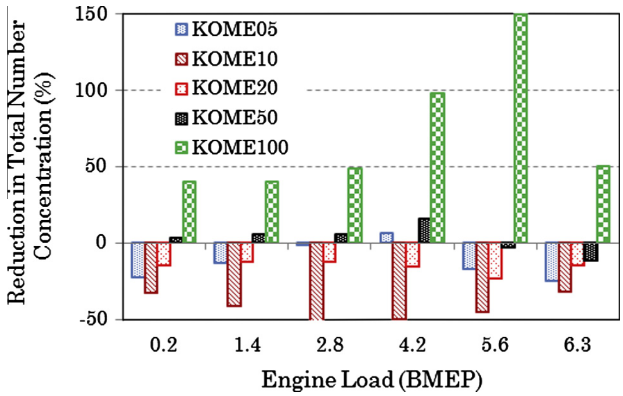

Fig. 8. Average reduction in total particle number concentration for Karanja biodiesel blends with respect to diesel at different engine loads.

mode particulate concentration for KOME100 (Fig. 3) is responsible for comparative reduction of CMD and increase of total number concentration in comparison to mineral diesel and biodiesel blends. At higher engine loads, requirement of higher fuel quantity for biodiesel (due to its lower calorific value) extends the combustion in expansion stoke. Larger amount of particulates may be produced during diffusion combustion at low temperature prevailing in later part of expansion stroke. Since these particles are formed later in the expansion stroke, when cylinder pressure is comparatively lower, chances of particulate coagulation may be lower. Hence increase in the number concentration of nuclei mode particles is observed for KOME100, which results in reduction of CMD.

Fig. 7 shows the variation of total particulate number in the size range of 5.6–560 nm for Karanja biodiesel blends with varying engine loads and speeds. Lower blends of biodiesel have lower total particulate number concentration in comparison to biodiesel. Total number concentration of particulates was found to be lowest for KOME10. Total number concentration of KOME05 was very close to mineral diesel at all engine operating conditions. KOME100 has highest total number of particulates at all engine operating conditions. At higher engine speeds and loads, total number concentration and variation in total number concentration for KOME100 was very large in comparison to other test fuels (Fig. 7(e) and (f)). Inhomogeneous mixing of fuel and air due to poor spray characteristics of KOME100 is responsible for these large variations. Fig. 8 shows average reduction in total particulate number concentration at varying engine load for different Karanja biodiesel blends with respect to baseline mineral diesel. Lower biodiesel blends showed reduction in total particulate number concentration however number concentration increased for KOME50 and KOME100. Zhu et al. reported higher total particulate number concentration for B100 in comparison to mineral diesel at 1800 rpm in BMEP range of 0.8–7.0 bar [20]. It was also reported that the difference in total number concentration of biodiesel and mineral diesel was high at intermediate loads and the number concentration for diesel and biodiesel were comparable at rated load and lower load conditions [20], which is consistent with the trends observed in present experimental investigation. Poor spray characteristics of biodiesel due to higher viscosity, density, surface tension and lower volatility may be responsible for increase in total particulate number emissions. Lower volatility of biodiesel can also contribute towards higher nano-particle formation. At rated engine load (Fig. 8), difference in the total number concentration of KOME100 and other fuels reduces because the air-fuel mixing of biodiesel improves due to higher in-cylinder temperatures and pressures at the time of fuel injection, which moderates the effect of fuel's higher viscosity and poor volatility. With cooling of exhaust, biodiesel vapors may condense and adsorb onto the nano-particles, reflecting an increase as well as change in profile of nano-particles [23].

4. Conclusions

Variations in particulate size-number distribution, size-surface area distribution and total particulate numbers emitted with changing engine speed and load for various Karanja biodiesel blends was experimentally investigated in an unmodified engine. Peak number concentration of particulates increased with increasing engine speed for all test fuels. At lower engine speeds, average size of particulates was considerably smaller for biodiesel blends as compared to mineral diesel however at higher engine speeds, average particulate sizes were comparable for all test fuels. In unmodified engine, KOME100 showed highest total particulate number emissions at all engine operating conditions. Other biodiesel blends showed relatively lower or comparable total particulate number emissions vis-a-vis baseline mineral diesel. Total particulate numbers were lowest for KOME10 among all test fuels. It shows that blending smaller concentration of Karanja biodiesel (upto 20%) can be effectively used to reduce the particulate number emissions, apart from other benefits.

Acknowledgements

Research grant support provided by Shell Global Solutions, Netherlands and Shell Technology India Private Limited for conducting this research is gratefully acknowledged. Support provided by Council of Scientific and Industrial Research (CSIR), Government of India under the Senior Research Associate (Pool Scientist) scheme to Dr. Atul Dhar for conducting this research is also acknowledged.

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