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Effect of Multiple Injections on Particulate Size-Number Distributions in a Common Rail Direct Injection Engine Fueled with Karanja Biodiesel Blends

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ABSTRACT

Use of alternative fuels, and reduction of particulate and NOx emissions are major challenges for making diesel engines environmentally benign. Measures adopted for reducing gravimetric particulate emissions necessarily always do not reduce particulate number concentration, which is strongly related with adverse health effects. Current emission norms in some parts of the world limit particulate number concentration along with particulate mass. In this scenario, it becomes important to investigate effect of fuel injection parameters and fuel injection strategies such as pilot injections on particulate size-number distribution. A single cylinder research engine is used to evaluate the effect of different fuel injection strategies and injection timings (for pilot and main injections) on particulate size-number distribution and total particulate numbers. Experiments were conducted at two fuel injection pressures (500 and 1000 bar) for different injection timings for biofuels (20% and 50% Karanja biodiesel blends) and the results are compared with baseline data of mineral diesel. Particulate number-size distribution decreases with increasing fuel injection pressure. For a fixed pilot injection timing, particulate number-size distribution increases with retarded main injection for all test fuels. Total particulate number concentration of biodiesel blends is lower than mineral diesel. Utilization of 20% blend of Karanja biodiesel results in highest reduction of particulate number emissions at retarded start of injection timing.

INTRODUCTION

Diesel engines are extensively used in transportation sector as well as for stationary applications because of their high thermal efficiency and robustness. Due to heterogeneous mixing of fuel and air, particulate emissions are high in diesel engines [1,2,3]. Recent refinements in diesel engine technology such as use of very high fuel injection pressures, turbo-charging etc. has resulted in considerable reduction in mass emissions of particulates. These technological interventions have made diesel engines significantly cleaner in last couple of decades however reduction in number of nucleation mode particles has not been quite significant [4,5,6]. Many studies have reported increase in nuclei mode particles from diesel engines with advanced technologies [7-8]. New emission legislations implemented worldwide also consider a strong correlation between number concentration and harmful impact of nano-particles on human health thereby they put a limit on particulate numbers. EURO-V (September 2011) and EURO-VI emission legislations put a limit of of 6.0×10^{11} (#/km) in addition to the limit on mass emission of particulates [9].

Formation of particulates depend on physical and chemical properties of fuels, process of air-fuel mixing and condition of the cylinder charge during combustion in rich premixed reaction zones, where particulate precursors are formed [10]. Due to complex dependency of particulate size-number distribution on these factors, several researchers have carried experimental evaluation of the effect of these factors on particulate number-size distribution [11,12,13,14,15,16,17].

Tan et al. observed that with increasing biodiesel concentration in the fuel, the number of nucleation mode particles increases and the particle size at peak concentration becomes larger, however the number of accumulation mode particles decreases at most of the operating conditions [11]. Zhu et al. reported that with increase in oxygen content of the fuel, soluble organic fraction of the particles increases and mean diameter of the particles becomes smaller [12]. Agarwal et al. reported increase in particle number concentration at lower engine loads and vice versa with 20% biodiesel blend [13]. Kawano et al. reported that the size-number distribution of accumulation mode particles of biodiesel shifts to smaller sizes vis-à-vis diesel, and peak of particle size-number distribution was almost constant for varying engine loads. On increasing the engine load, peak number concentration of particulate increases in case of diesel and peak concentration of the particulates decreases for RME [14]. Zhu et al. reported that at all engine loads, the total number concentration of particulates from biodiesel was higher than mineral diesel [15]. Addition of ethanol/ methanol in biodiesel reduces the total number concentration of the particulates to dramatically below the level of mineral diesel [16]. Desantes et al. reported that increasing the fuel injection pressure reduces the accumulation mode particle numbers and favored the formation of nuclei mode particles [17]. They also reported that advanced start of injection (SOI) slightly reduced the accumulation mode particle concentration without shifting the position of the peak number concentration [17]. Puzun et al. observed that size of vast majority of particulates emitted from high-pressure common rail diesel engine were lower than 300 nm for biodiesel as well as for diesel [18]. They also reported that at low and medium engine loads with increasing concentration of biodiesel in the test fuel, particle size distribution changes from single peak to double peak distribution; the number of particles in nucleation mode increase; concentration of particles larger than 50 nm diameter in accumulation mode decrease and the peak concentration position shifts towards smaller particle sizes [18]. Majority of the diesel engines used today employ common rail direct injection (CRDI) technology. This technology uses very high injection pressures, upto 1600 bars and is highly flexible in terms of fuel injection. Multiple injections are possible along with the flexibility of changing start of injection for main and pilot injections, in response to the changing load and speed conditions. There are however very few studies on understanding the effect of fuel injection strategies and pilot injections on the particulate size-number distribution of diesel and biodiesel fueled engines.

Due to shortage of edible oils in India, biodiesel policy of Indian government focuses on utilization of non-edible oils for biodiesel production [19]. Karanja oil is one of the major non-edible tree borne feedstock species for producing biodiesel in India on large scale as it is well adapted to local climatic conditions and is available in surplus quantities in length and breadth of the country [20]. Therefore, in this research, effect of varying fuel injection pressure, and SOI timings for pilot and main injection on the particulate size-number distribution has been experimentally investigated on a single cylinder research engine equipped with common rail direct injection (CRDI) system fueled with Karanja biodiesel blends vis-à-vis mineral diesel.

EXPERIMENTAL SETUP

Effect of fuel injection pressure, SOI timings for main and pilot injection and injection strategy on the particulate emissions was evaluated on a single cylinder research engine (AVL List GmbH, Graz, Austria; 5402) equipped with a CRDI fuel injection system. Technical specifications of the test engine are given in table 1. It is a naturally aspirated engine without the provision of EGR. Engine management system (EMS) of this engine has complete flexibility for control and measurement of fuel injection pressures and injection timings, when operating in manual mode. In map mode operation of the EMS, fuel injection parameters are automatically selected according to pre-defined operational maps. For present investigation, engine was operated in manual mode with user defined control of injection pressures, SOI for main and pilot injection and injection strategy. This test engine is representative of the most modern research tools available for CRDI engine mapping and calibration. During the experiments, temperature of fuel was maintained at 20°C using fuel conditioning unit (AVL List GmbH, Graz, Austria; 753CH). Temperature of the coolant was maintained at 80°C by coolant conditioning system (Yantrashilpa, India; YS4027). For all operating conditions, pressure and temperature of the lubricating oil were maintained at 3.5 bars and 90°C respectively using lubricating oil conditioning system (Yantrashilpa, India; YS4312).

Table 1. Specifications of the test engine

Engine type	AVL 5402
Number of cylinders	1
Cylinder bore/ stroke (mm)	85/ 90
Swept volume (cc)	510.7
Compression ratio	17.5
Number of valves	4
Inlet ports	Tangential and swirl inlet port
Maximum power (kW)	6
Fuel injection system	Common rail direct injection
Fuel injection pressure (bar)	200-1400

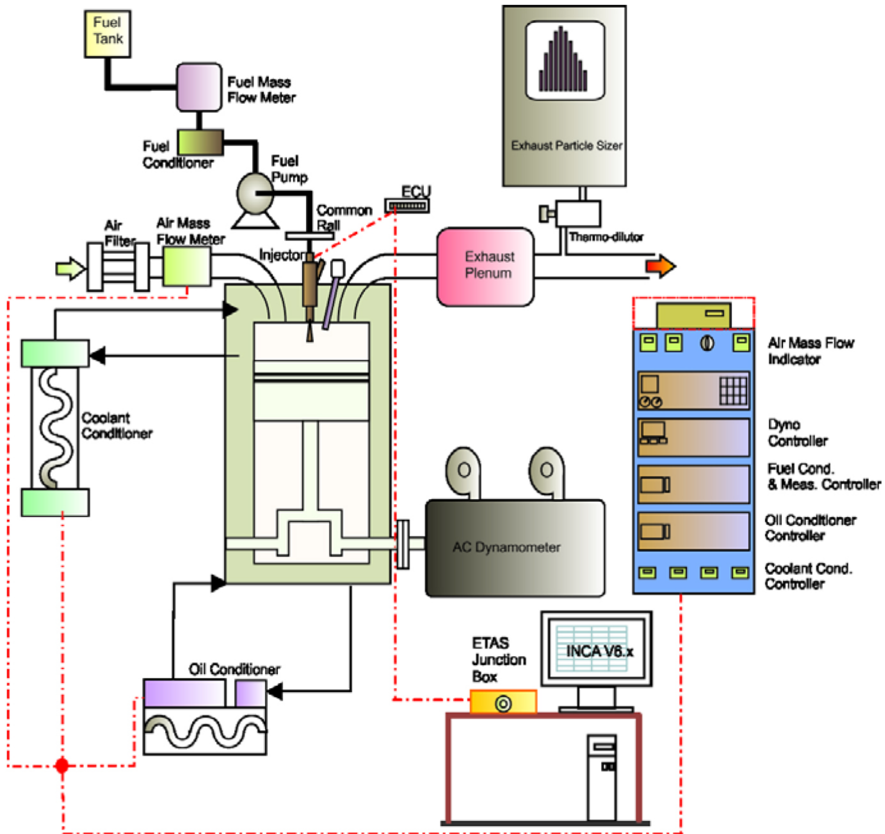

Figure 1. Schematic of the experimental setup

For particulate size-number characterization, Engine Exhaust Particle Sizer™ Spectrometer (EEPS) (TSI Inc.; EEPS3090) was employed. It can measure particle sizes ranging from 5.6- 560 nm with a maximum concentration of 10^8 particles/cc of the exhaust. It has sizing resolution of 2 decades, 16 channels per decade comprising of total 32 channels. Number concentration of particulates in the raw engine exhaust is higher than the measuring range of the instrument, hence the exhaust is diluted (235 times for the present investigation) by filtered atmospheric air (by HEPA filter) using a rotating disk thermo-diluter (Matter Engineering AG, UK; MD19-2E) before supplying the exhaust gas sample to EEPS for particulate measurement. Concentration of particulates in the diluted exhaust was measured. Distribution of particle size-number distribution in the engine out exhaust was calculated by accounting for the dilution factor. Particle size-number distribution data presented in the results and discussion section are an average of 60 successive measurements and the error bars correspond to the standard deviation of the measurement.

Effect of multiple injections on the particulate size-number distribution was investigated at 500 and 1000 bars fuel injection pressure by varying the SOI timings of pilot and main injections. These pressures were chosen because the fuel injection is done at similar type of injection pressures in modern production grade CRDI engines. Experiments were performed for 20% and 50% Karanja oil methyl ester (KOME: Biodiesel) blended with mineral diesel (KOME20 and KOME50) at constant engine speed (1500 rpm) vis-à-vis baseline data of mineral diesel. The engine speed was also kept constant in order to keep the number of experiments run under limit and to understand the particulate formation behavior at one speed. Important physical properties of test fuels are given in table 2. Fuel energy input to the engine was kept constant for all engine operating conditions equivalent to air fuel ratio (AFR) of 23 for mineral diesel. Engine operating point corresponding to approximately 5 bar brake mean effective pressure (BMEP) engine load at medium speed (1500 rpm) was selected for detailed investigation of the effect of injection parameters on particulate number emissions. This load condition typically represents the condition at which an engine would operate most of time in any real life situation. In double injection mode, only 10% fuel quantity was injected in the pilot injection and remaining 90% fuel quantity was injected in the main injection.

Table 2. Physical properties of the test fuels

Fuel	Viscosity@40°C (cSt)	Density (g/cm^3)	LHV (MJ/kg)
Diesel	2.78	0.831	43.79
KOME20	3.11	0.841	42.57
KOME50	3.51	0.856	40.8

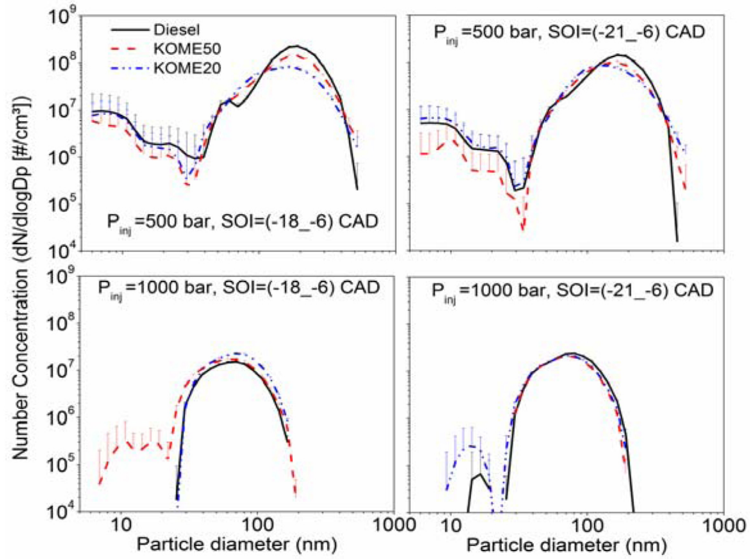

Figure 2. Variation of particulate size-number distribution with varying injection pressure and position of pilot injection (main injection fixed at 6 crank angle degrees BTDC)

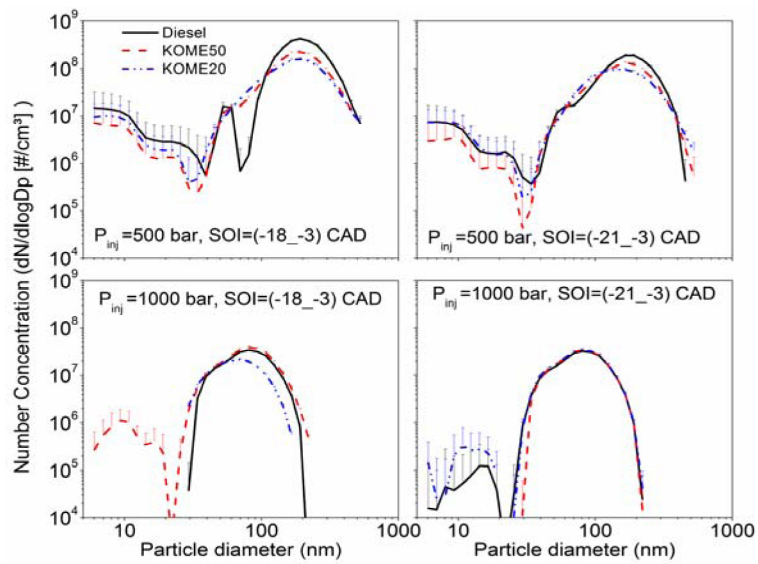

Figure 3. Variation of particulate size-number distribution with varying injection pressure and position of pilot injection (with main injection fixed at 3 crank angle degrees BTDC)

RESULTS AND DISCUSSION

Particulate size-number distribution was measured after thermal stabilization of the engine at each test condition. Advancement of start of injection timings was limited by peak rate of pressure rise limit of 10 (bar/deg). SOMI timings were not retarded after TDC as beyond it, a clear drop in BMEP was observed. At 500 and 100 bar fuel injection pressures, common fuel injection parameters were chosen for the sake of comparison and are shown below in figure 2 and 3. These figures show the particle size and number distributions for the start of main injection (SOMI) fixed at 6 and 3° CA before top dead center (BTDC) respectively with varying start of pilot injections (SOPI). Three test fuels, namely diesel, KOME20 and KOME50 have been investigated.

Negative values of injection timings in the figures represent start of injection BTDC. It can be observed from figure 2 that concentration of larger size particles significantly reduce with increasing fuel injection pressure for all test fuels. At both fuel injection pressures, advancing the SOPI timing from 18° CA to 21°CA BTDC results in reduced number of particles and the magnitude of reduction is higher for larger diameter particles i.e. accumulation mode particles. Figure 3 shows the effect of fuel injection pressure and SOPI timing at 3° CA before TDC SOMI timing. It can be observed that by

Table 3. Variation of performance and emission parameters at 500 bar injection pressure

SOPI	-18	-18	-18	-18	-18	-21	-21	-21	-21	-21	-21
SOMI	-12	-9	-6	-3	0	-15	-12	-9	-6	-3	0
Fuel	BMEP (bar)										
Diesel	5.1	5.1	4.9	4.8	4.8	5.1	5.0	5.0	4.9	4.8	4.7
KOME50	5.2	5.2	5.1	5.0	4.8	5.1	5.1	5.1	5.0	5.0	4.9
KOME20	5.2	5.1	5.0	4.9	4.8	5.1	5.1	5.0	4.9	4.9	4.8
	BSFC(g/kWh)										
Diesel	305.3	307.3	317.8	325.9	329.4	304.5	310.2	315.4	322.1	326.4	332.7
KOME50	321.6	325.8	333.7	339.0	351.5	327.3	327.8	332.7	340.1	339.8	347.8
KOME20	308.6	315.1	324.1	331.3	338.7	313.4	316.4	323.8	329.0	331.7	339.5
	BSNOx (g/kWh)										
Diesel	15.1	12.4	10.4	8.4	7.1	18.0	15.1	12.7	10.0	7.9	6.7
KOME50	14.2	12.0	9.6	7.9	6.8	16.9	14.2	11.2	9.2	7.5	6.4
KOME20	15.6	13.4	11.3	9.1	7.6	19.0	16.0	13.2	10.6	8.7	7.5

increasing the fuel injection pressure from 500 bars to 1000 bars, particle size-number distribution decreases in nucleation mode as well as in accumulation mode for all test fuels. Concentration of nuclei mode particles is very low for mineral diesel and KOME20 at 18°CA BTDC SOPI timing and 21°CA BTDC SOPI timing for KOME50 at 1000 bars fuel injection pressure (figure 2 and figure 3). At 1000 bars fuel injection pressure at 21°CA BTDC SOPI and 6°CA BTDC SOMI timings, size-number distribution of particles for biodiesel blends is lower than that of mineral diesel however the trend is opposite at 18°CA BTDC SOPI timing (figure 2). This is due to relatively lower volatility of Karanja biodiesel vis-à-vis mineral diesel. Poor evaporation characacterisitcs combined with higher viscosity of biodiesel increases the time required for air-fuel mixing for biodiesel blends in comparison to mineral diesel. In-cylinder conditions for fuel injected in main injection are directly affected by combustion of the fuel injected during pilot injection. Time delay between the two injection pulses is very critical for controlling the formation of particulate matter (PM) during multiple injections [21]. For achieving effective reduction in soot formation by split injection, optimization of time difference between the two injection pulses is very critical. Separation between two injection pulses should be long enough so that the soot formation region of the first injection pulse is not replenished with the incoming fuel from the second injection pulse. Separation between the two injection pulses (pilot and main) should be short enough to ensure high temperature and pressure conditions for the incoming fuel (during main injection) are available for faster combustion of the fuel, resulting in lower soot formation [21]. Particulate diameter corresponding to the peak concentration in the size-number distribution increases by increasing the seperation between main and pilot injection pulses for all test fuels at both fuel injection pressures. Peak number distribution diameter for biodiesel particulates was lower than mineral diesel particulates at 500 bars fuel injection pressure. Peak concentration diameter for all test fuels was however almost same at 1000 bars fuel injection pressure. Tan et al. [11] also observed that the particle size at peak concentration becomes smaller with increasing biodiesel concentration in the fuel (i.e. increasing fuel oxygen content) at most of the operating conditions. At 500 bars fuel injection pressure, concentration of nuclei mode particles was generally lower for biodiesl blends in comparison to mineral diesel however at 1000 bars fuel injection pressure, concentration of nuclei mode particles was higher for biodiesel blends. Increasing the fuel injection pressure results in reduction of number concentration of nuclei mode particles for mineral diesel as well as for biodiesel blends. However this reduction for mineral diesel was higher than reduction for biodiesel blends which resulted in comparatively higher concentration of nuclei mode particles for biodiesel blend fueled operation of the engine at 1000 bar injection pressure. This indicates that increasing the fuel injection pressure is more effective in improving the air-fuel mixing of mineral diesel compared to biodiesel blends, and causes greater reduction in nuclei mode particulate formation for mineral diesel. Tables 3 and 4 show the variation of selective performance and emission parameters such as BMEP, brake specific fuel consumption (bsfc) and NOx emissions with different pilot and main SOI timings at 500 and 1000 bars injection pressures respectively.

In the investigated range of SOMI timing variation, BMEP decreased with retarding SOMI timings at both injection pressures for all test fuels. BSFC increased with retarding SOMI timings due to reduction in BMEP because fuel energy input to the engine was constant for all engine operating conditions. Increase in BSNOx emissions was seen with advancing SOPI and SOMI timings for all test fuels. Retarding the fuel injection timings reduces the peak in-cylinder temperature and pressure attained during combustion, which results in lower NOx emissions. NOx emissions for KOME50 and KOME20 were higher than mineral diesel and highest NOx emissions were observed with KOME20 fueled engine. Comparison of tables 3 and 4 shows that at same combination of SOPI and SOMI timings, BSNOx was higher for 1000 bar fuel injection pressure in comparison to the 500 bar fuel injection pressure because of superior mixing of fuel and air at higher injection pressure, leading to increased peak temperature in the cylinder charge during combustion.

Average size of emitted particulates was derived by size-distribution. Average size of particles represented by count mean diameter provides a basis for comparing the overall size

Table 4. Variation of performance and emission parameters at 1000 bar injection pressure

SOPI	-18	-18	-18	-18	-18	-18	-21	-21	-21	-21	-21	-21
SOMI	-6	-4.5	-3	-1.5	0	1.5	-9	-7.5	-6	-4.5	-3	0
Fuel	BMEP (bar)											
Diesel	5.1	5.0	5.0	5.0	4.9	4.9	5.2	5.2	5.2	5.1	5.2	5.1
KOME50	5.3	5.2	5.2	5.1	5.0	5.0	5.3	5.2	5.2	5.2	5.1	5.2
KOME20	5.2	5.2	5.1	5.1	5.0	5.0	5.2	5.2	5.2	5.2	5.1	5.1
	BSFC(g/kWh)											
Diesel	309.3	311.0	311.4	314.5	318.5	321.0	304.4	304.4	304.6	305.5	306.5	310.6
KOME50	320.8	323.5	325.4	330.7	335.0	337.4	316.6	322.6	322.7	325.7	327.9	326.9
KOME20	308.5	313.6	317.8	318.8	320.6	322.8	308.5	311.0	312.5	313.6	315.4	317.4
	BSNOx (g/kWh)											
Diesel	12.7	11.3	9.9	9.0	8.1	7.4	18.8	17.1	14.3	12.6	11.0	9.8
KOME50	12.4	11.6	10.7	9.4	8.2	7.6	19.0	16.0	13.2	10.6	8.7	7.5
KOME20	13.4	12.4	10.7	9.6	8.7	8.1	19.3	17.0	15.2	13.1	11.1	10.2

of emitted particulates from different engine operating conditions [14, 22].

Figure 4 shows the variation of count mean diameter (CMD) of particulates with varying fuel injection pressures, SOPI and SOMI injection timings for biodiesel blends and mineral diesel. CMD of particulates was lower than 100 nm for 1000 bars fuel injection pressure for all test fuels. At 500 bars fuel injection pressure, CMD of the particulates was in the range of 100-200 nm for all test fuels. Advancing the SOPI timing reduces the CMD in the entire range of SOMI timings for both injection pressures for all test fuels. This happens because the fuel injected in pilot injection gets enough time to combust and create hot and high pressure environment for the fuel injected during the main injection. Advance SOPI timings gives more time therefore the results are more favorable.

For a fixed SOPI timing, advancing the SOMI timing results in reduction of CMD. CMD of the biodiesel blends is seen to be lower than mineral diesel. Lower CMD indicates lower concentration of accumulation mode particles and/ or higher concentration of nuclei mode particles for biodiesel blends in comparison to mineral diesel. CMD of KOME50 was higher than KOME20 due to higher concentration of larger size accumulation mode particles (figure 4). For advanced SOMI timings, peak in-cylinder temperatures are high, which facilitates oxidation/ re-burning of the particulates. Accumulation of particulates is also high at lower in-cylinder temperatures occurring during retarded SOMI timings. These factors increase the CMD for retarded SOMI timings. Tinsdale et al. also reported reduction in mean particulate size with increasing biodiesel concentration (upto 30% v/v) in the fuel [23], similar to the present observation. Song et al. reported that biodiesel soot undergoes devolatilization of surface oxygen groups bonded at the edge sites, providing the nascent reactive sites for continuing oxidation by analyzing reactivity, structure and surface functionality of soot [24]. Therefore, the presence of surface oxygen functionality may facilitate surface burning which occurs progressively from the outer most periphery. This results in appreciable diameter change, by which, the outer layers are removed and the inner amorphous core is left [25]. This difference in surface oxygen functionality is responsible for lower CMD of Karanja biodiesel blends in comparison to mineral diesel.

Figure 5 shows the variation of total particulate numbers for biodiesel blends vis-à-vis mineral diesel at different fuel injection pressures and SOMI timings. Increasing the injection pressure from 500 bars to 1000 bars reduces the total number of particles an order of magnitude (As seen from the Y-axis scale). Retarding the SOMI timing results in increased total particle concentration for all test fuels. Advancing the SOPI timing results in lower total particle number concentration for all fuels for both injection pressures. The reasons for these two features are same as the ones given for explaining figure 4. At 500 bars fuel injection pressure, total particulate concentration for biodiesel blends was lower than mineral diesel for all injection timings (figure 5a-b). This difference in total particle number was more significant for retarded SOMI timings. At 1000 bars fuel injection pressure, differences in the total particulate concentration of biodiesel and diesel blends were not significant. For advanced SOMI timings, total particulate number concentration of biodiesel blends and mineral diesel were almost same. Biodiesel blends do not show sufficient reduction at advanced SOMI timing vis-à-vis mineral diesel because reduction in concentration due to fuel's oxygen content is offset by relatively inferior fuel-air mixing (due to larger droplet sizes formed by higher viscosity of biodiesel) and relatively lower evaporation of biodiesel, when incylinder pressure is relatively lower during the main injection event. Total particulate number concentration of KOME50 was higher than KOME20 as comparatively higher concentration of biodiesel in test fuel results in inferior fuel mixing and vaporization due to higher viscosity, density and lower volatility of biodiesel in comparison to mineral diesel.

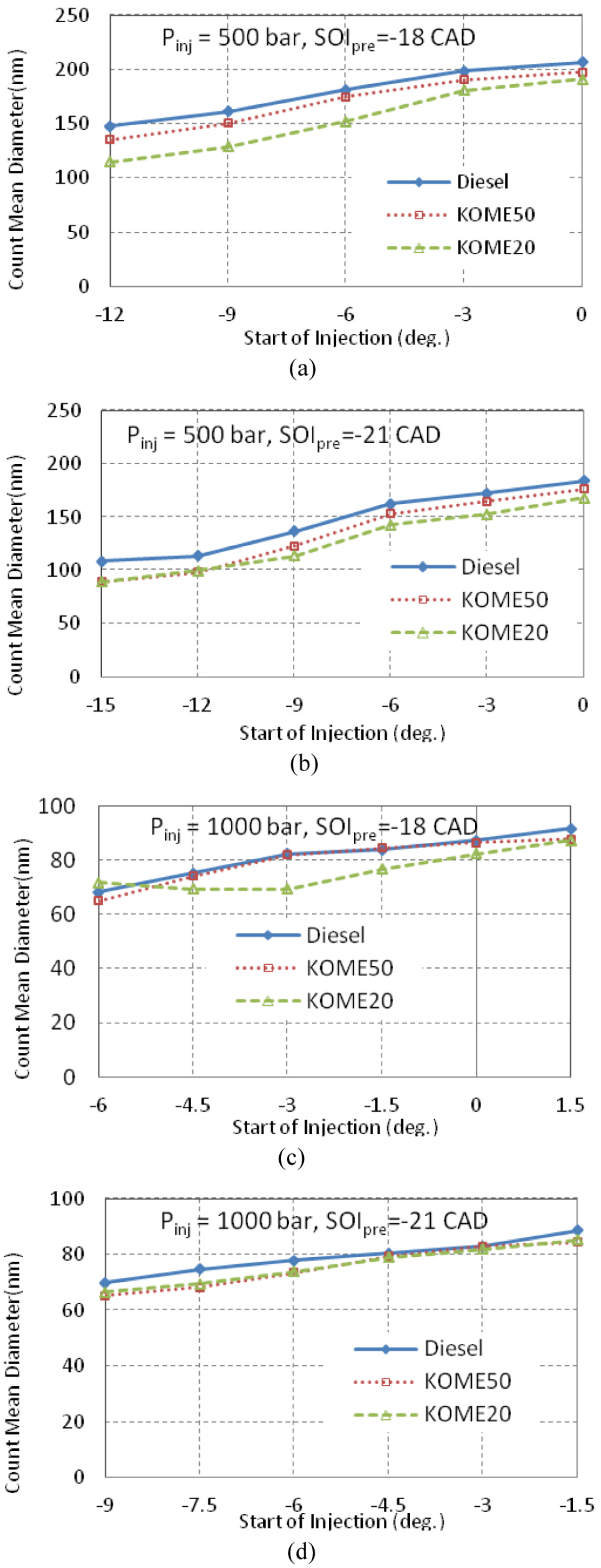

Figure 4. Variation of count mean diameter of particles with SOMI timing for biodiesel blends and diesel

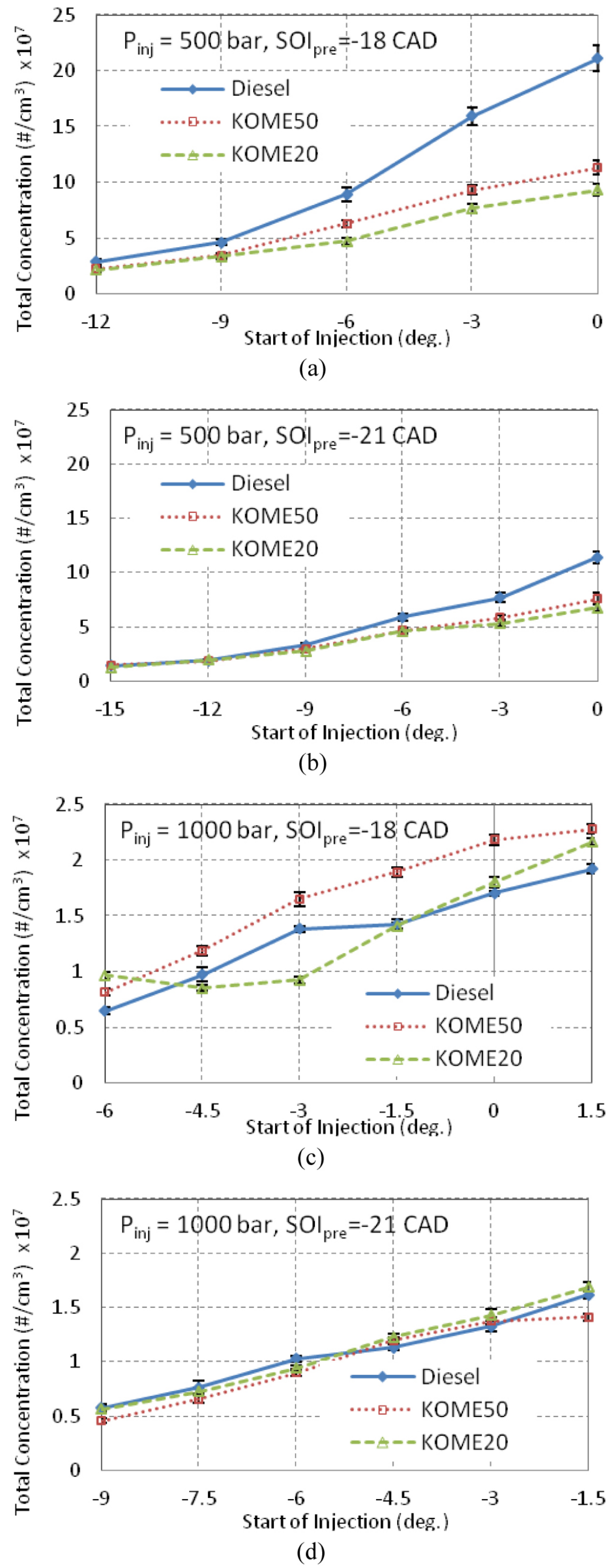

Figure 5. Variation of total number of particles with SOMI timing for biodiesel blends and diesel

CONCLUSIONS

Effect of multiple injections on particulate size-number distribution were investigated for biodiesel blends and mineral diesel fuelled single cylinder research engine at 500 bars and 1000 bars fuel injection pressures. Important findings are:

• Numbers of larger size particles reduced significantly with increasing fuel injection pressure for all test fuels.

• Total number concentration of particulates reduced with advanced pilot injections. Peak concentration in the particle size-number distribution increases by increasing the seperation between pilot injection and main injection pulses.

• Count mean diameter of particulates emitted during biodiesel blend fueled engine operation was lower than mineral diesel.

• Among the three tested fuels, KOME20 showed lowest total particulate number emissions. Particulate number concentration increased with further increase of biodiesel concentration in the fuel.

• Injection timings may be retarded for biodiesel blend fuelled engine as it can offset the increase in NOx emissions while keeping the particulate emissions comparable to mineral diesel fueled operation.

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