Effect of Fuel Injection Pressure and Injection Timing of Karanja Biodiesel Blends on Fuel Spray, Engine Performance, Emissions and Combustion Characteristics

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Abstract

In this investigation, effect of 10, 20 and 50% Karanja biodiesel blends on injection rate, atomization, engine performance, emissions and combustion characteristics of common rail direct injection (CRDI) fuel injection system were evaluated in a single cylinder research engine with CRDI at 300, 500, 750 and 1000 bar fuel injection pressures at different start of injection timings and constant engine speed of 1500 rpm. The durationof fuel injection slightly decreased with increasing blend ratio of biodiesel (Karanja Oil Methyl Ester: KOME) and significantly decreases with increasing fuel injection pressure. The injection rate profile and sauter mean diameter (D_{32}) of the fuel droplets are influenced by the injection pressure. Increasing fuel injection pressure generally improves the thermal efficiency of the test fuels. Sauter mean diameter (D_{32}) and arithmetic mean diameter (D_{10}) decreased with decreasing Karanja biodiesel content in the blend and significantly increased for higher blends due to relatively higher fuel density and viscosity. Maximum thermal efficiency was observed at the same injection timing for biodiesel blends and mineral diesel. Lower Karanja biodiesel blends (upto 20%) showed lower brake specific hydrocarbon (BSHC) and carbon monoxide (BSCO) emissions in comparison to mineral diesel. For lower Karanja biodiesel blends, combustion duration was shorter than mineral diesel however at higher fuel injection pressures, combustion duration of 50% blend was longer than mineral diesel. Upto 10% Karanja biodiesel blends in a CRDI engines improves brake thermal efficiency and reduces emissions, without any requirement of hardware changes or ECU recalibration.

Keywords: Combustion; Karanja biodiesel; Emissions; Fuel injection pressure; Injection timing.

1. Introduction

Diesel engines are extensively used and dominating power sources for road transport sector due to their higher thermal efficiency, operational reliability, robustness, lower hydrocarbon (HC) and carbon monoxide (CO) emissions. In the last two decades, biodiesel has emerged as a well-accepted alternative fuel to mineral diesel because its utilization requires insignificant modifications in the engine hardware. With advanced fuel injection systems, fuel injection pressures have risen by an order of magnitude in comparison to older mechanical fuel injection systems. It is therefore very important to investigate the effect of fuel injection pressure on comparative performance, emissions and combustion characteristic of biodiesel and mineral diesel for effective utilization of biodiesel in modern CI engines. Boudy *et al.* estimated the influence of fuel properties on the pressure–wave in the injector feed pipe and injector mass flow rate by the modeling for a common-rail diesel injection system and reported that amount of injected mass was mainly affected by the density of the fuel [1]. Yehliu *et al.* observed 12% higher brake specific fuel consumption (BSFC) for B100 (with 15% lower calorific value than diesel) in comparison to mineral diesel in a four-cylinder CRDI engine [2]. Suryawanshi *et al.* reported slightly higher brake thermal efficiency (BTE) for *Pongamia* biodiesel blends in comparison to mineral diesel. They also reported that retarding the injection timing by 4 crank angle degrees resulted in minor improvement in thermal efficiency at part loads and no change at full load [3]. Grimaldi *et al.* obtained slightly higher engine efficiency, when the engine was fuelled with biodiesel, particularly at high load in comparison to mineral diesel fuelled engine [4]. Zhu *et al.* reported that oxygenated fuels including biodiesel, biodiesel-ethanol and biodiesel-methanol blends gave better BTE at all engine operating conditions vis-à-vis mineral diesel [5]. Gumus *et al.* observed that BTE of mineral diesel decreased as fuel injection pressures increased from 18 to 24 MPa but for biodiesel, it increased with increasing fuel injection pressure at full load [6]. Highest achieved BTE for diesel (at 18 MPa injection pressure) and biodiesel (at 24 MPa injection pressure) were 32.1 and 41.3% respectively [6]. Agarwal *et al.* reported that higher fuel injection pressure leads to a longer spray tip penetration and larger spray area compared to lower fuel injection pressures after identical elapsed time after the start of injection (SOI) for Karanja biodiesel blends and diesel [7].

Baldassarri *et al.* reported 10% reduction in CO emissions by fuelling the bus engines by B20 vis-à-vis mineral diesel [8]. Zhu *et al.* observed lower BSCO emissions for biodiesel fuelled engine in comparison to diesel fuelled engine [5]. Kousoulidou *et al.* observed that biodiesel does not have any effect on CO emission levels vis-à-vis mineral diesel in an engine equipped with common rail injection system [9]. Suh *et al.* reported reduction in CO emissions for biodiesel blends as well as mineral diesel with advanced injection timing [10]. Wang *et al.* observed that 35% soybean biodiesel blend resulted in reduced HC emissions in comparison to mineral diesel [11]. Gumus *et al.* reported that NOx emissions generally decreased with increasing fuel injection pressure but the trend was not regular and significant [6].

Kuti *et al.* investigated the spray formation and combustion characteristics of Palm biodiesel and mineral diesel by using a CRDI system in a constant volume chamber [12]. They observed longer liquid length for biodiesel in comparison of mineral diesel due to higher boiling range of biodiesel [12]. Ignition delay (ID) was shorter for biodiesel due to its higher cetane number. ID reduced with increasing fuel injection pressure and decreasing nozzle diameter [12]. Suh *et al.* reported similar combustion pressure and rate of heat release for 5% blend of soybean biodiesel and mineral diesel [10]. Lee *et al.* investigated the effect of biodiesel blended fuels (Biodiesel derived from unpolished rice and soyabean) on the atomization and combustion characteristics for a common-rail single-cylinder engine. It was reported that higher surface tension and viscosity of the biodiesel causes lower Weber number and decreases injection velocity of biodiesel-blended fuels respectively, and result in increased mean droplet size diameter with increasing blend ratio. The spray tip penetration was observed to be longer for higher injection pressure. Higher cetane number of biodiesel causes shorter ignition delay, which was responsible for increased peak combustion pressure with an increase of the biodiesel blend ratio. With increasing biodiesel blend ratio, lower HC and CO were observed, whereas NOx emissions increased, possibly because of fuel oxygen in biodiesel coupled to shorter ignition delay of biodiesel. [13]. Experimental study by Can concluded that despite earlier start of injection, combustion and engine performance characteristics proved that the ignition delay decreased with addition of biodiesel at all engine loads with relatively earlier SOC due to higher cetane number of biodiesel [14].

Depending upon the local availability, different feedstocks are being promoted worldwide for production of biodiesel. Biodiesel policy of India encourages utilization of non-edible oils for biodiesel production because India has shortage of edible oils [15]. Karanja also known as *pongamia pinnata*, is a tree borne oil seed, which naturally grows in almost whole of south Asia [16-18]. Karanja is one of the important nitrogen fixing trees (NFTs) which produces seeds containing 30-40% oil (w/w). It is planted as an ornamental and shade tree but now-a-days, it has emerged as an important resource for oil, which can be used for production of biodiesel. The average seed yield of Karanja is about 4-9 tons/ha [19]. Based on review of several experimental studies, Ashraful *et al.* concluded that Karanja biodiesel is superior because of its cetane number, higher brake thermal efficiency, lower BSFC and lower emission characteristics in comparison to various other non-edible feedstock based biodiesels [20]. Its utilization for large scale biodiesel production will ensure stability of supply because it is well adapted to local climatic conditions. In this study, effect of Karanja biodiesel blends on engine performance, emissions and combustion characteristics have been experimentally investigated at different fuel injection pressure for exploring the prospects of Karanja biodiesel/ blends utilization in modern transport engines equipped with common rail direct injection (CRDI) fuel injection system. In addition to detailed engine investigations, spray studies have also been done.

2. Experimental Setup

2.1 Injection rate and spray droplet measuring system

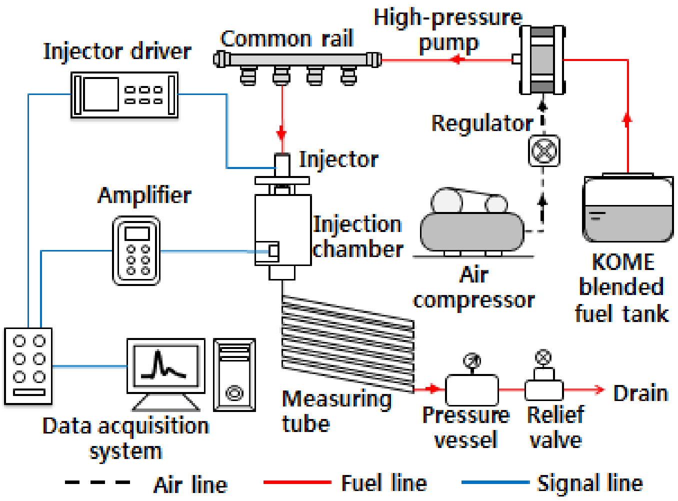
In order to investigate the injection rate of Karanja oil biodiesel, the injection rate measuring system was used for various injection pressure conditions as illustrated in Figure 1. This system is based on the pressure variation in a measuring tube, filled with biodiesel. When the high- pressure biodiesel is injected into the tube, the fuel creates pressure wave detected by a pressure sensor in the tube. During the fuel injection, the pressure in the tube was maintained constant at 20 bar. In the system, the line pressure was continuously measured by using the pressure sensor. In this test, 1000 fuel injections were carried out and the measurements were averaged.

Figure 2 shows the phase Doppler droplet analysis system, which comprises of a high-pressure fuel injection system, an Ar-Ion laser, a transmitter, a receiver, data acquisition and signal synchronizer system. To investigate the droplet size of Karanja biodiesel under varying injection pressure conditions, droplet measuring system with a 514.5 nm and 488 nm wavelengths were applied. As listed in Table 1, photomultiplier voltages and laser output were selected at 500V and 700mW, respectively. For measuring range of droplet size, cut-off range of the droplet sizes for spray measurement was set up from 2 μm to 75 μm. In this investigation, a 0.3 mm single hole nozzle with 0.8 mm hole depth was used in order to the prevent the interference of droplet coalescence between neighboring droplets due to multi-hole nozzle.

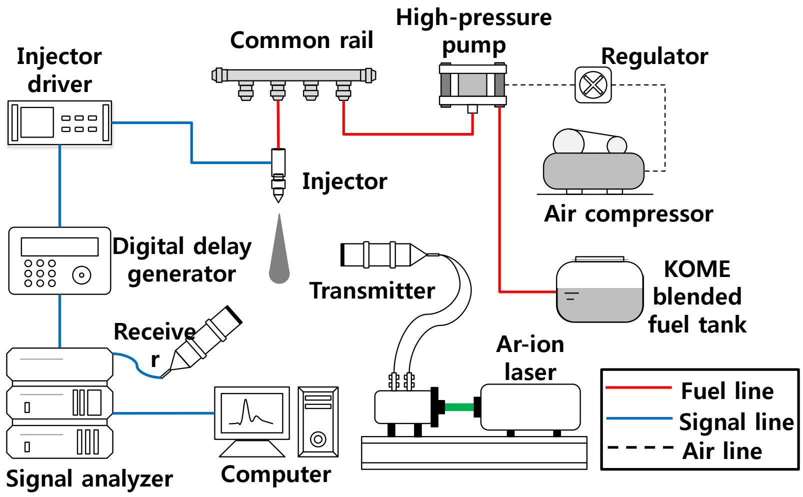
Table 1: Details of injection rate and spray droplet measurement systems

Injection rate measurement system	Fuel injection system	Common rail direct injection
	Injection rate meter	Bosch's procedure [21-23]
	Fuel injection pressure (bar)	300-1000
	Number of nozzle holes	6
	Nozzle hole diameter (mm)	0.131
	Measuring tube pressure (bar)	30
	Injected mass (mg)	12
Droplet measurement system	Light source	Ar-ion laser
	Wave length (nm)	514.5 nm, 488 nm
	Focal length (mm)	Transmitter: 500, Receiver: 250
	Collection angle (degrees)	30

	Fuel injection pressure(bar)	600-1000
	Number of holes	1
	Nozzle hole diameter (mm)	0.3
	Injected mass (mg)	12



(a) Injection rate measuring system



(b) Phase Doppler particle analyzer system

Figure 1: Injection rate and phase Doppler particle analyzer system

Schematic of the experimental setup used for evaluation of engine performance, emissions and combustion characteristics of test fuels at different fuel injection pressures is shown in Figure 2.

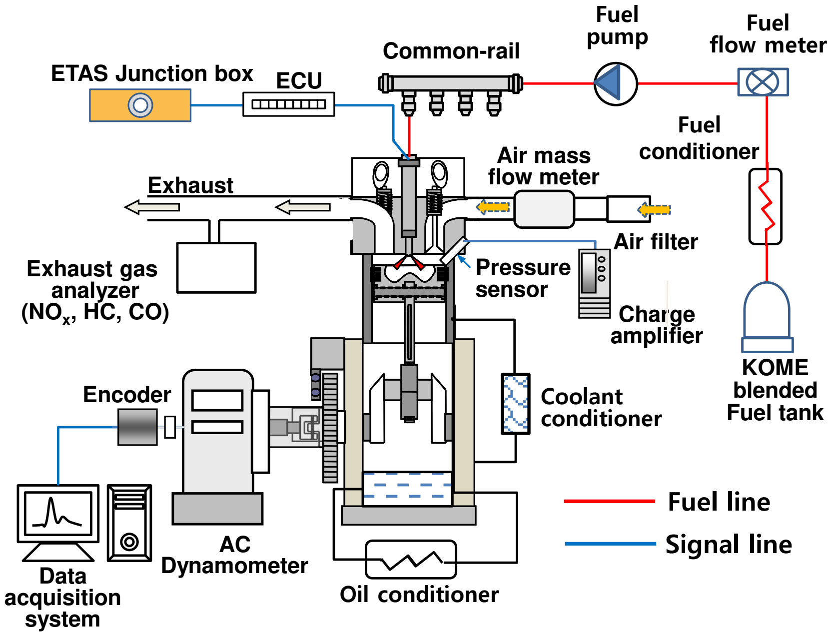


Figure 2: Schematic of the engine experimental setup

Effect of fuel injection pressure (FIP), start of injection (SOI) timing and injection strategy on the engine performance, emissions and combustion characteristics were evaluated using a single cylinder research engine (AVL List GmbH; 5402). This test engine was equipped with a common rail direct injection (CRDI) system. Detailed technical specifications of the test engine are given in Table 2. Engine performance, emissions and combustion characteristics of the test engine were investigated at 300, 500, 750 and 1000 bar FIPs and varying SOI timings. During the experiments, fuel temperature was maintained at 20°C using fuel conditioning unit (AVL List GmbH; 753CH). For these experiments, engine management system was operated in manual mode with user defined control of FIP, SOI timings and injected fuel quantity. Lubricating oil temperature and pressure were also maintained at 90°C and 3.5 bar respectively using an oil condition system (Yantrashilpa; YS4312). Coolant temperature was kept maintained at 80°C by coolant conditioning condition unit (Yantrashilpa; YS4027).

Air and fuel consumption rates were measured by rotary gas flow meter system (Elster Instromart; RVG G160) and a fuel flow meter (AVL List GmbH; Fuel Balance 733S.18) respectively. Raw engine emissions were measured by exhaust gas emissions analyser (AVL List GmbH; 444). Exhaust gas sample was passed through a moisture trap and a filter to arrest moisture condensation and particulates from entering the analyzer test cell. HC is measured in 'ppm of hexane equivalent'; NO measured in 'ppm' and CO, CO_2, and O_2 are measured in 'volume percentage'. Accuracy and measurement ranges of emission analyzer have been given in table 3. For comparison across different power ranges, data of raw emissions from the exhaust gas emission analyzer is converted to mass emissions i.e. brake specific emission using IS: 14273 code [24]. Cylinder pressure was measured by a water cooled piezoelectric pressure transducer (AVL List GmbH; QC34C) mounted flush in the cylinder head. Rotation of the crank shaft was recorded by an optical encoder (AVL List GmbH; 365CC/ 365X). For acquisition and analysis of cylinder pressure-crank angle data, a high speed data acquisition system (AVL List GmbH; Indismart-611) was used. Variation in cylinder pressure with crank angle was recorded for 200 consecutive engine cycles and then averaged for eliminating the effect of cycle-to-cycle variations. This averaged cylinder pressure data was used to calculate heat release rate, mass-burn fraction crank angles, combustion duration and other combustion related parameters.

Experiments were performed for mineral diesel, biodiesel and three biodiesel blends (KOME10, KOME20 and KOME50) at constant engine speed (1500 rpm). Important physical properties of test fuels are given in Table 4. Fuel energy injected into each engine cycle was kept constant for all engine operating conditions, which was equivalent to air-fuel ratio (AFR) of 23 using mineral diesel. Engine operating point corresponding to 5 bar brake mean effective pressure (BMEP) engine load and 1500 rpm engine speed was chosen for detailed investigations of the effect of FIP and SOI timings on particulate numbers emitted. Upper limit of advanced SOI timings at each FIPs was limited by peak rate of pressure rise limit (15 bar/deg). Lower limit of retarded SOI timings was limited by the lower selected limit of BMEP (4.5 bar).

Table 2: Specifications of the test engine

Engine Make, Model	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

Table 3. Measurement range, resolution and accuracy of the exhaust gas emission analyzer (AVL444)

Species	Range	Resolution	Accuracy
CO	0-10% vol.	0.01 vol. %	<0.6% vol.: ±0.03% vol. ≥0.6% vol.: ± 5% of ind. vol.
CO_2	0-20% vol.	0.1 vol. %	<10% vol.: ±0.5% vol. ≥10% vol.: ± 5% of ind. vol.
HC	0-20000 ppm	≤ 2000:1 ppm vol. ≤ 2000:10 ppm vol.	<200ppm vol.: ± 10 ppm vol. ≥200ppm vol.: ± 5% of ind. vol.
NO	0-5000 ppm	1 ppm vol.	<500ppm vol.: ± 50 ppm vol. ≥500ppm vol.: ± 10% of ind. vol.
O_2	0-22% vol.	0.01 vol. %	<2% vol.: ±0.1% vol. ≥2% vol.: ± 5% of ind. vol.

Important fuel properties of diesel, biodiesel and blends were measured in the laboratory. The instruments used for these measurements and the properties are given in Table 4.

Table 4: Important physical properties of test fuels

Properties	**Instruments Used**	**KOME100**	**KOME50**	**KOME20**	**KOME10**	**Diesel**
Viscosity @ 40°C (cSt)	Kinematic Viscometer (Setavis)	4.42	3.51	3.11	3.04	2.78
Density @ 40°C (g/cm^3)	Portable Density Meter (KEM Electronics)	0.881	0.856	0.841	0.836	0.831
Lower Calorific Value (MJ/kg)	Bomb Calorimeter (Parr)	37.98	40.8	42.57	43.18	43.79
Cetane Number	CRF Engine (CI Unit)	50.8	--	--	--	51.2

3. Results and Discussion

Effect of fuel injection pressure and SOI timing on engine performance, emissions and combustion characteristics of Karanja biodiesel and blends with mineral diesel (KOME50, KOME20 and KOME10) vis-à-vis baseline mineral diesel were investigated at 1500 rpm speed in a single cylinder research engine. For the sake of clarity, the experiments on Spray are discussed first, followed by the results on engine experiments.

3.1 Injection rate and spray atomization

Figure 3 shows the effects of fuel injection pressure on the injection duration for different biodiesel blends. As seen from the figure 3, injection duration of KOME blends and mineral diesel decreases with increasing fuel injection pressure. The rate of reduction of injection duration gradually reduced with increasing injection pressure (as observed for 750 bar and 1000 bar injection pressures). In case of relatively lower pressures (350 bar and 500 bar), there were large differences between the two injection pressures compared to that of 750 bar and 1000 bar injection pressures. Therefore for identical fuel injection quantity, higher injection pressure would require shorter injection duration because of higher injection velocity from the nozzle exit. This is due to larger pressure difference between the fuel injection pressure and the ambient pressure in the engine combustion chamber. On comparing the blending ratio of KOME biodiesel blends and conventional diesel, the fuel injection duration slightly reduced with increasing blending ratio of KOME biodiesel blends. Possible reason is that higher biodiesel blends have higher density due to higher density of biodiesel. Higher density for higher biodiesel blends results in shorter injection duration however reduction in rate of injection duration is smaller compared to that of KOME. Boudy *et al.* also concluded from their modeling results of CRDI system that density of fuel is the main property, which influences injection parameters greatly such as total injected fuel mass, pressure wave etc. [1].

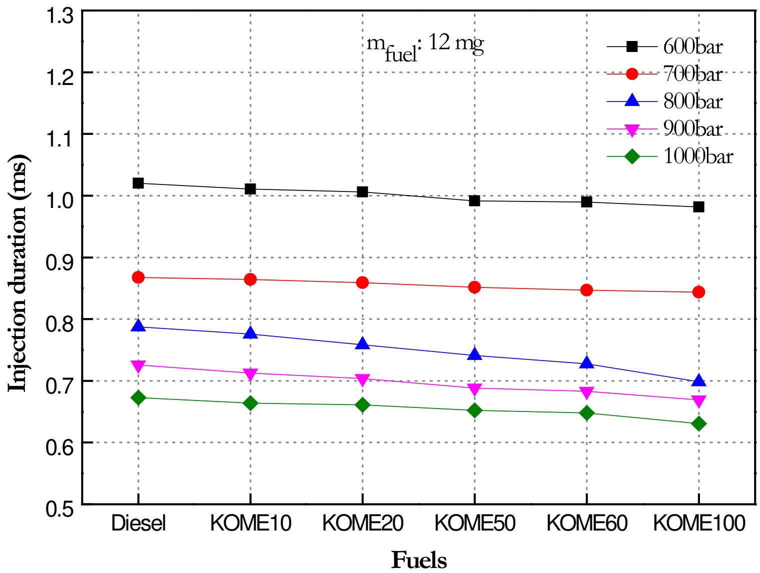


Figure 3: Effects of varying fuel injection pressure on the injection duration for different biodiesel blends.

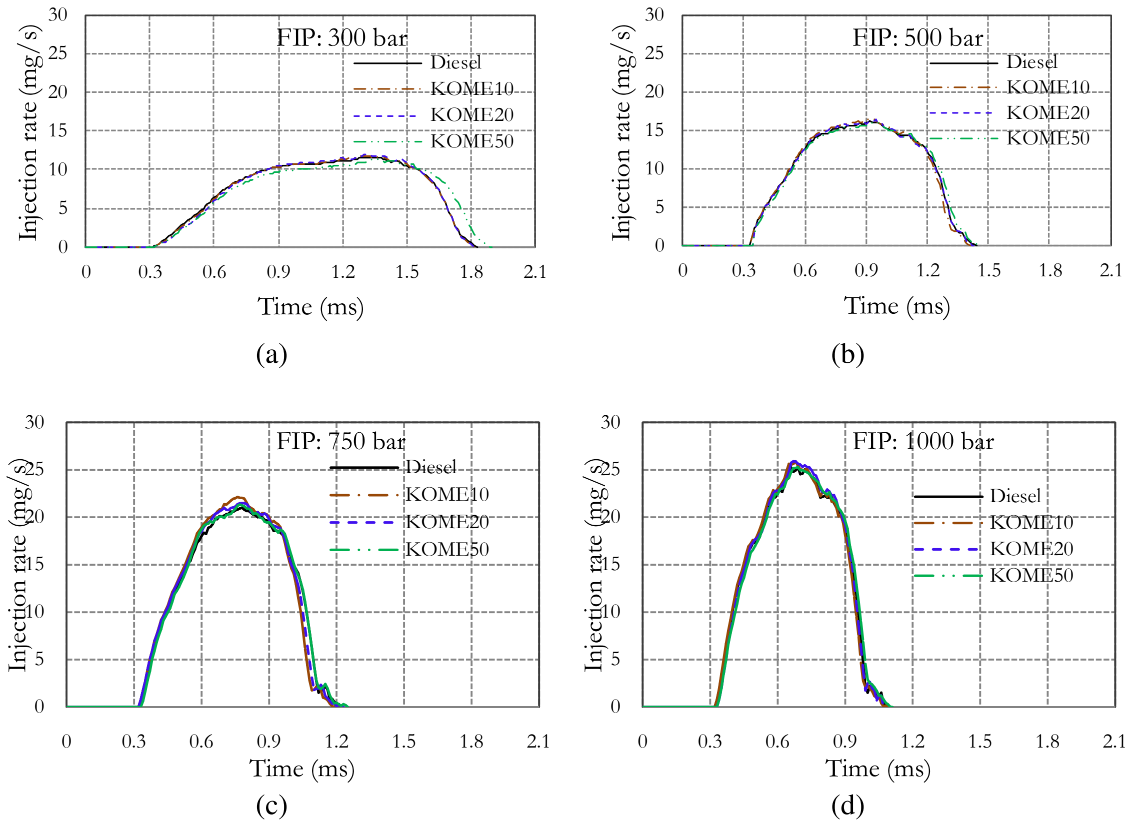
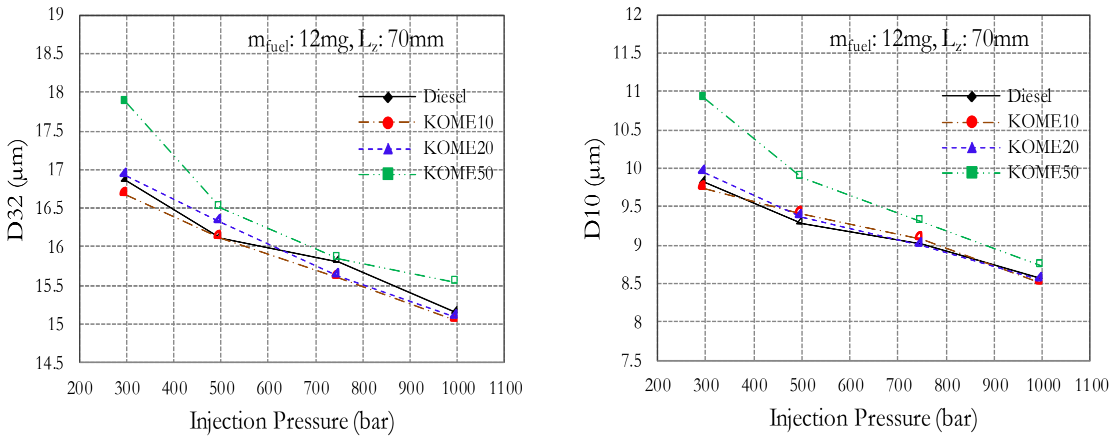


Figure 4: Effects of fuel injection pressure on the injection rate for different biodiesel blends at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs.

Figure 4 illustrates the effects of fuel injection pressure on the injection rate for different KOME biodiesel blends. As shown in Figure 4, fuel injection duration shortened with increasing injection pressure and the peak injection rate increased with increasing fuel injection pressure.

Figure 5 shows the droplet size in the fuel sprays of KOME blends and conventional diesel measured by Phase Doppler Particle Analyzer (PDPA) system. As illustrated in this Figure5, droplet sizes were represented by Sauter mean diameter (SMD or D_{32}) and arithmetic mean diameter (D_{10}) increased with increase in KOME biodiesel concentration in the test blend.



(a) Sauter mean diameter (b) Arithmetic mean diameter

Figure 5: Atomization characteristics of KOME blends and diesel fuel

Upon comparing the effect of fuel injection pressure on the droplet sizes, one can observe that the mean diameter of KOME blends and mineral diesel were significantly different at higher blending ratio due to significantly different fuel density and viscosity. KOME 50 demonstrated significantly larger droplet sizes than mineral diesel as shown in Figure 5 (a) and (b) [25].

3.2 Engine performance characteristics

Effects of FIP and SOI timings on engine performance are assessed by comparing the BSFC and BTE variations vis-a-vis SOI timings for Karanja biodiesel blends and baseline mineral diesel.

Brake Specific Fuel Consumption

Figure 6shows the BSFC variation with changing SOI timings in single injection mode at 300, 500, 750 and 1000 bar FIPs for various blends of Karanja biodiesel vis-à-vis baseline mineral diesel. Negative values of SOI timings represent start of injection before top dead center (TDC) (SOI BTDC) and positive values represent start of injection after the TDC (SOI ATDC).

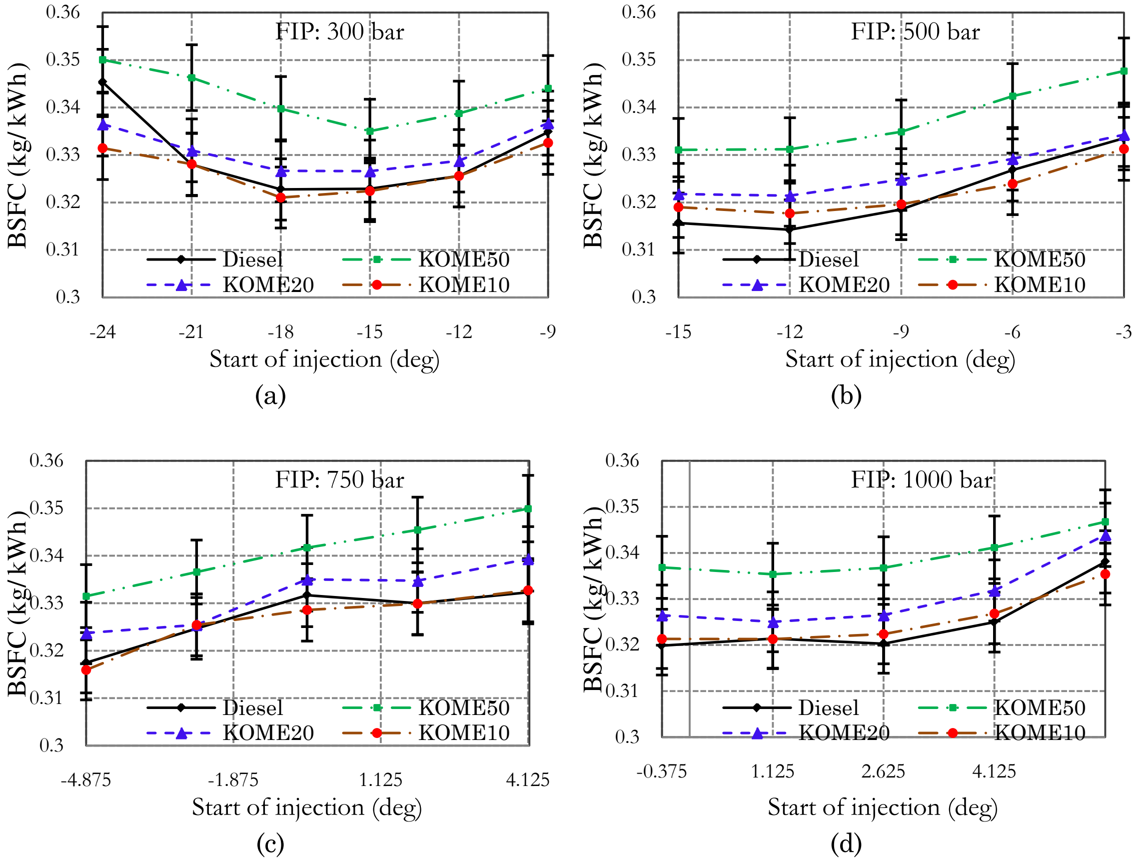


Figure 6: Variations in BSFC with varying SOI timings for biodiesel blends vis-à-vis mineral diesel at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs

In single injection mode, BSFC for KOME50 and KOME20 were higher than mineral diesel (Figure 6). BSFC of KOME10 was almost similar to mineral diesel due to insignificant difference in physical properties of the test fuels. Reduction of calorific value of test fuel with increasing concentration of Karanja biodiesel was responsible for increase in BSFC for KOME50 and KOME20 blends. These results are in conformity with similar measurement obtained by Yehliu et al. [2], which were primarily due to approximately 13% lower calorific value of biodiesel compared to mineral diesel. At 300 and 500 bar FIPs, BSFC was lowest at -18°CA and -15°CA SOI timings respectively for all test fuels. At 750 bar FIP, BSFC was lowest for -4.875°CA SOI timing. At 1000 bar FIP, BSFC was lowest at 1.125 °CA SOI timing for all test fuels. At higher FIPs, advancement of SOI timings were restricted to -4.875 and -0.375°CA at 750 and 1000 bar FIPs respectively due to very high rate of pressure rise (ROPR). Figure 6 shows that

SOI timing corresponding to minimum BSFC retarded with increasing FIP for all test fuels. Park *et al.* also reported similar findings that at higher FIPs in single injection mode (600 and 1200 bar); fuel energy was most efficiently converted into useful power, when SOI timing was closer to TDC [26]. Increasing FIP reduces the injection duration, leading to finer spray droplets, which improve the air-fuel mixing, thus increasing the premixed heat release, which results in significant portion of heat being released during the compression stroke, especially for advanced SOI timings. Higher heat release during the compression stroke is counter-productive beyond a certain limit because it works against the piston, which is trying to reach TDC in the compression stroke, hence minimum BSFC is observed for retarded SOI timings with increasing FIPs.

Brake Thermal Efficiency

Figure 7 shows the variation of BTE of Karanja biodiesel blends with SOI timings at different FIPs vis-à-vis baseline mineral diesel.

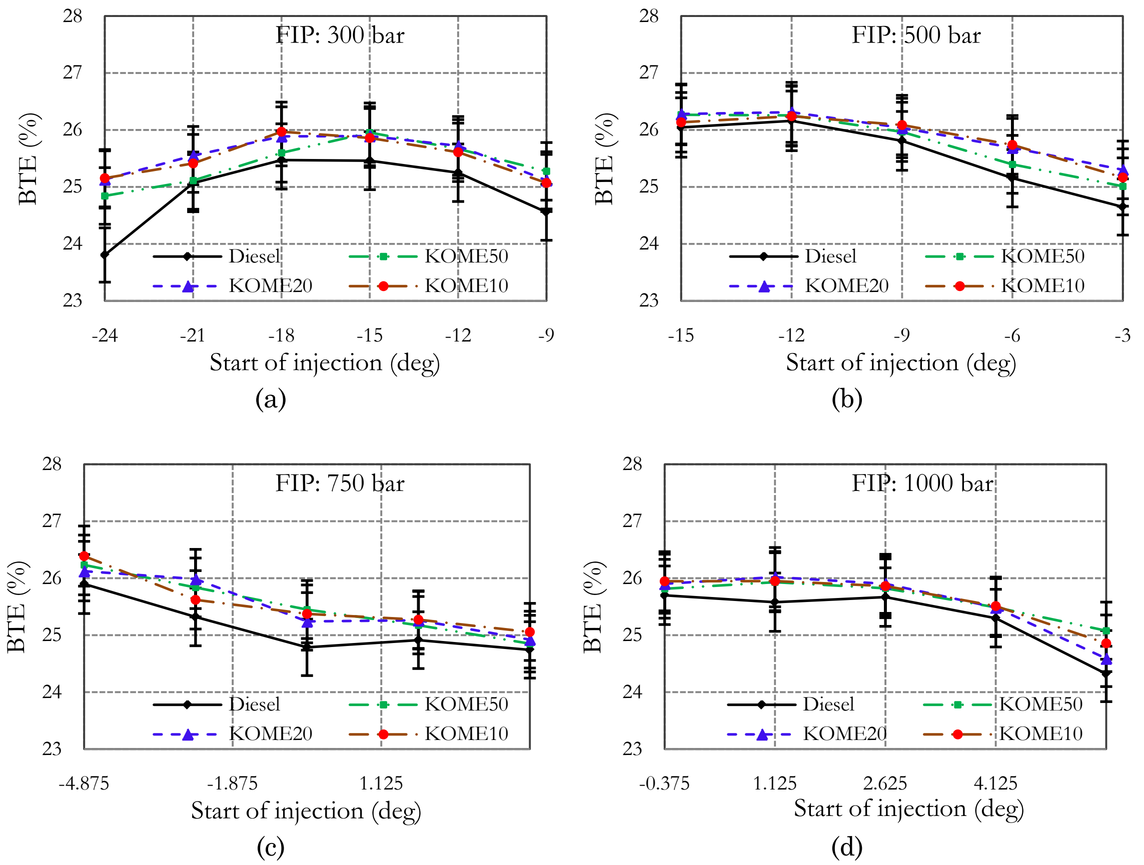


Figure 7: Variation in BTE with varying SOI timings for biodiesel blends vis-à-vis mineral diesel at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs

Figure 7 shows that the thermal efficiency of Karanja biodiesel blends is higher than mineral diesel at all engine operating conditions. These results are consistent with previous research results [3-6], Suryawanshi et al. also observed increase in BTE for Pongamia biodiesel compared to mineral diesel [3]. Thermal efficiency of lower biodiesel blends (KOME10 and KOME20) was higher than KOME50. BTE was highest at -15°CA SOI timing for all test fuels for 300 and 500 bar FIPs. At a fixed SOI timing, it was observed that increasing FIP generally improves the thermal efficiency of test fuels. Increasing FIP was more effective in increasing BTE of mineral diesel in comparison to Karanja biodiesel blends, which suggests that higher injection pressure is more effective in improving the spray characteristics of fuels with lower viscosity, which is mineral diesel in this case. However, Gumus et al. reported decrease in BTE of mineral diesel with increase in fuel injection pressures from 180 to 240 bar while for biodiesel, found increased with increasing fuel injection pressure at full load [6]. It was also observed that for all test fuels, SOI timing corresponding to maximum BTE shifts towards TDC with increasing FIP. Suryawanshi et al. also reported that retarding injection timing by 4° crank angle resulted in minor improvement in thermal efficiency at part loads [3].

3.3 Emissions characteristics

Effect of FIP and SOI timings on carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx) emissions were investigated by maintaining input fuel energy per cycle constant for all test fuels. Brake specific emissions of regulated gases for Karanja biodiesel blends are compared with mineral diesel for varying fuel injection parameters.

Carbon Monoxide Emissions

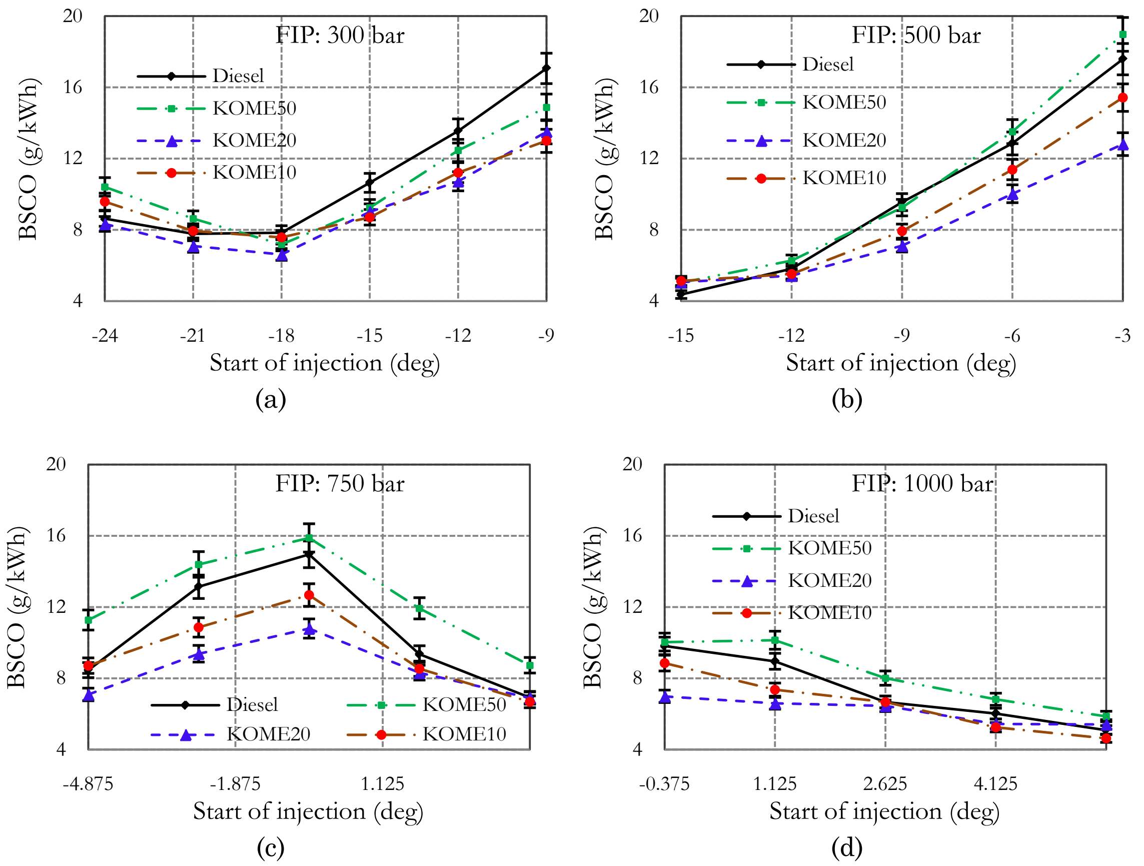


Figure 8:Variations in BSCO emissions with varying SOI timings for biodiesel blends vis-à-vis mineral diesel at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIP

Figure 8 shows the variations in brake specific carbon monoxide (BSCO) emissions from Karanja biodiesel blends with varying SOI timings at different FIPs vis-à-vis baseline mineral diesel. At 300 bar FIP, BSCO emissions were lowest at -18°CA SOI timing for all test fuels and they increased when injection timing was further retarded (Figure 8(a)). Advanced SOI timings beyond -18°CA resulted in greater formation of fuel rich zones due to increased ignition delay and relatively inferior atomization of fuel injected during early phase of fuel injection, when in-cylinder pressure and temperature were comparatively lower. These fuel rich zones may be the reason for increased CO emissions. At 500 bar FIP, BSCO emissions were lowest at -15°CA SOI timing which increased with retarded SOI timings (Figure 8(b)). Retarding the injection resulted in increase of BSCO as it pushed the majority of combustion into the expansion stroke, which reduced the temperature and pressure during the later part of the combustion in the expansion stroke, thus increasing CO formation. Suh *et al.* also observed rapid increase in CO emission for retarded injection timing due to a longer heat release [10]. At 750 and 1000 bar FIPs, CO emissions were high when SOI timings were close to TDC and it decreased with retarding SOI timings. This is probably due to wall impingement of high pressure fuel spray droplets. Park *et al.* also reported that injection under high pressure close to TDC results in wall impingement of fuel droplets and/ or accumulation of some fuel in the squish area of the piston [26], which causes relatively inferior mixing of fuel with air, resulting in increased CO and HC emissions. At all FIPs, BSCO emissions of KOME20 and KOME10 were lower than mineral diesel. Similar trends for lower BSCO for biodiesel were also reported by Zhu *et al.* [5]. However, another scientific study by Baldassarri *et al.* reported 10% reduction in CO emissions for B20 vis-à-vis mineral diesel [8]. BSCO emissions of KOME50 were higher relative to lower biodiesel blends and at higher injection pressures and they were even higher than mineral diesel. It indicates that higher concentration of Karanja biodiesel in test fuel causes issues related to fuel atomization and mixing, which can possibly offset improvement in the combustion due to oxygenated fuels. At a fixed SOI timing, increasing FIP results in reduction in BSCO emissions due to improvement in fuel-air mixing because of finer fuel spray droplets formation at higher FIP.

Unburnt Hydrocarbon Emissions

Figure 9shows the variation in brake specific hydrocarbon (BSHC) emissions of Karanja biodiesel blends vis-à-vis SOI timings at different FIPs in comparison to baseline mineral diesel.

BSHC emissions increased with retarded SOI timings for 300 and 500 bar FIPs for all test fuels. Retarding SOI timings lowers the in-cylinder pressure and temperature during combustion, which in-turn increases engine-out HC emissions. At 750 and 1000 bar FIPs, BSHC emissions increased sharply, when the SOI timings were close to TDC.

This was possibly due to piston wall impingement of the fuel sprays because during the fuel injection, piston remains very close to the injector tip. Similar increase in HC emissions levels was also reported by Park *et al.* when SOI timings were close to TDC at 600 and 1200 bar FIPs [26].

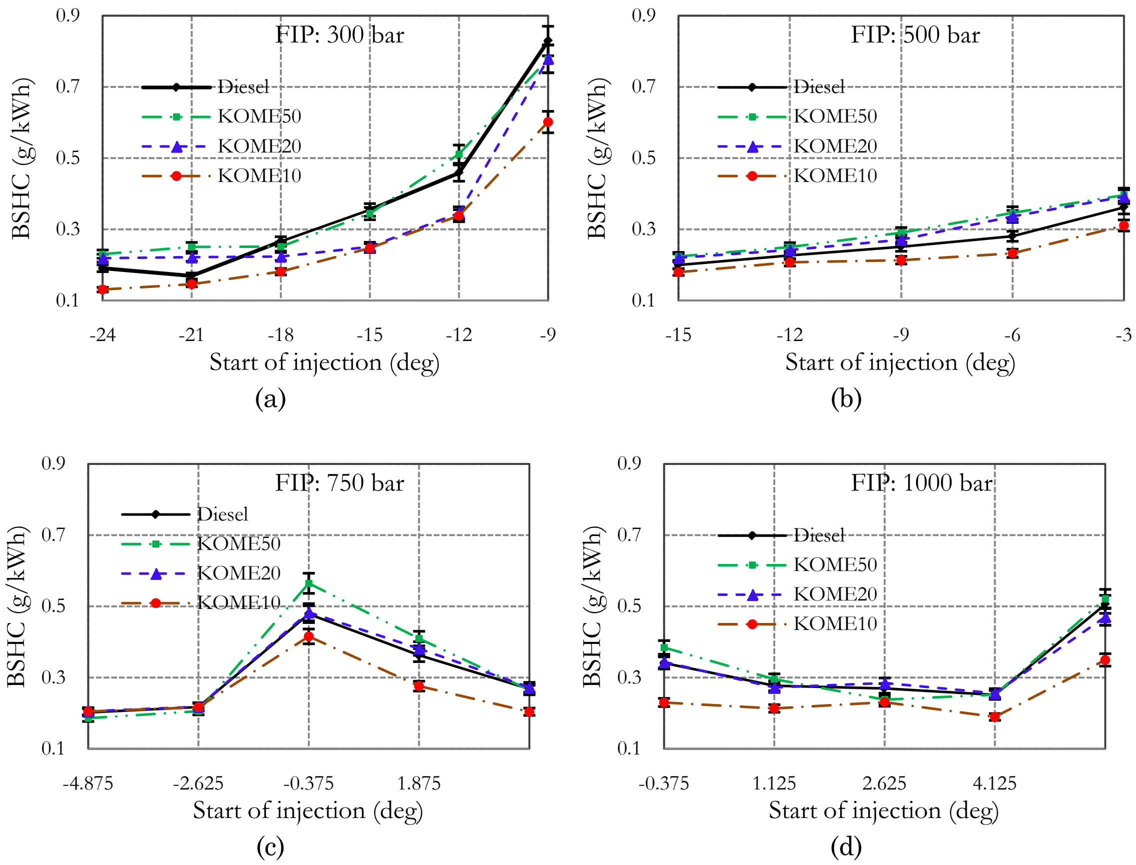


Figure 9: Variations in BSHC emissions with varying SOI timings for biodiesel blends vis-à-vis mineral diesel at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs

BHSC emissions start increasing again with further retarded SOI timings at 1000 bar FIP after 4.125°CA SOI timings(Figure 9(d)) due to lower in-cylinder temperature and pressure observed during combustion, which increase the formation of unburnt hydrocarbons. BSHC emissions for KOME10 were lower than mineral diesel but BSHC emissions of KOME50 and KOME20 were higher than mineral diesel. Ashraful *et al.* also concluded similar trend of lower HC emission for lower Karanja biodiesel blends in their review of various experimental studies [20]. It shows that smaller concentrations of biodiesel improves combustion without adversely affecting the air-fuel mixing significantly however higher concentrations of biodiesel adversely affects the atomization of the fuel sprays and subsequent air-fuel mixing.

Oxides of Nitrogen Emissions

Figure 10shows the variations in brake specific NOx (BSNOx) emissions vis-à-vis SOI timings for different FIPs.

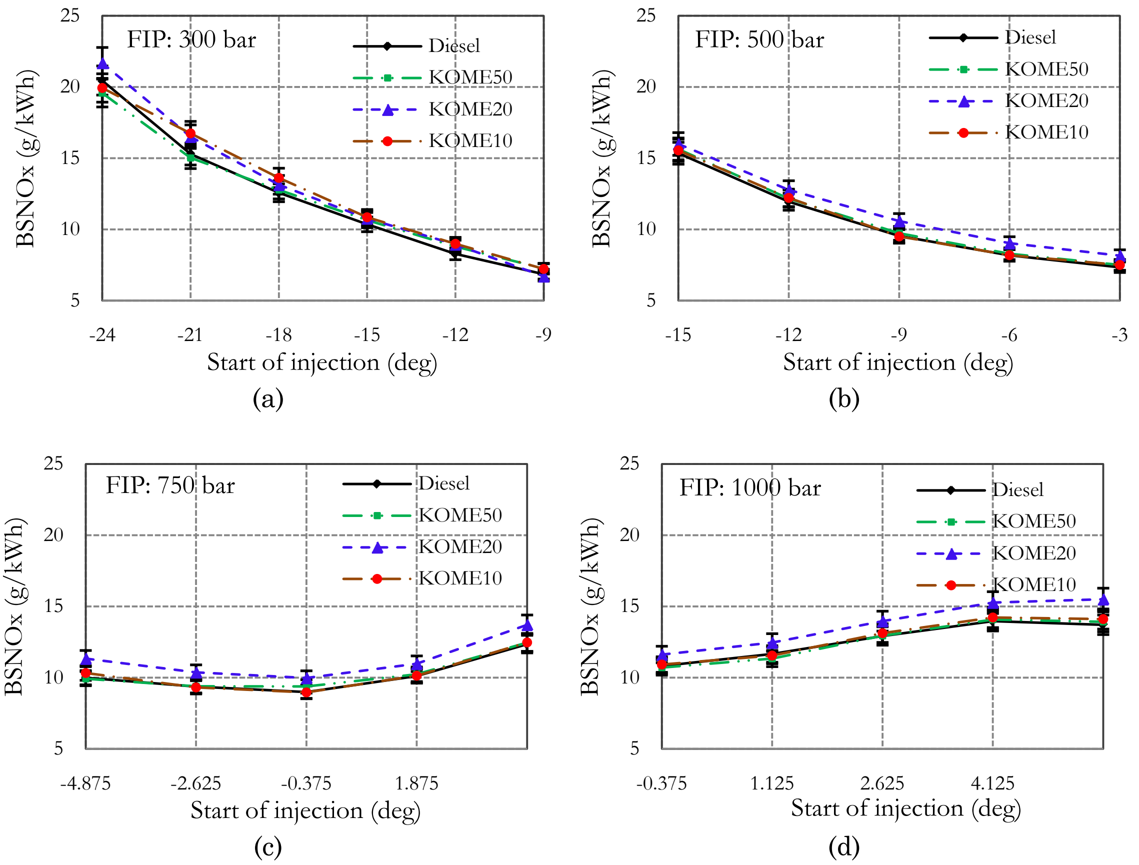


Figure 10: Variations in BSNOx emissions with varying SOI timings for biodiesel blends vis-à-vis mineral diesel at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs

At 300 and 500 bar FIPs, BSNOx emissions decreased with retarded SOI timings for all test fuels. At 750 and 1000 bar FIPs, BSNOx emissions were lowest when the SOI timings were close to TDC but started increasing again when SOI timings were further retarded after TDC for all test fuels (Figure 10(c)-(d)). It was observed that at these FIPs, peak of premixed heat release also keeps on increasing, when SOI timings are retarded upto 4.125 °CA ATDC (Figure 10). Both, peaks of premixed heat release and BSNOx concentration reduce when SOI timings were retarded to 5.625 °CA from 4.125

°CA. BSNOx emissions of KOME20 and KOME10 were higher than mineral diesel for all FIPs. NOx emissions of KOME50 were lower than KOME20 and KOME10 and almost equal to mineral diesel. At BMEP comparable to present study and 450 bar FIP (-3.89 °CA SOI timing), Yehliu *et al.* reported almost comparable BSNOx emissions [2]. These values and trends are consistent with trend of BSNOx emissions at 500 bar FIP in this study. At the same SOI, increasing fuel injection pressure increases NOx emissions significantly. Similar trend of NOx emissions were also reported by Ye et al. [30]. However, Ye et al. also concluded that at the same SOI and fuel injection pressure, biodiesel fueling also increases NOx emissions significantly. Many studies have reported that effect of biodiesel on NOx emissions depends on the type of engine used as well as engine operating conditions [2, 27-29]. These trends are observed due to the combined effect of fuel spray characteristics deterioration because of higher fuel viscosity and higher fuel density and differences in the ignition quality due to the differences in the chemical structure of mineral diesel and biodiesel.

3.4 Combustion characteristics

Effects of FIP and SOI timings on the combustion characteristics of KOME50, KOME20 and KOME10 vis-à-vis mineral diesel were analyzed by measuring in-cylinder pressure w.r.t. crank angle position in a single cylinder research engine equipped with CRDI fuel injection system. Measured pressure data of 200 consecutive engine cycles were averaged in order to eliminate the effect of cyclic variations of combustion parameters and the experimental data was analyzed to calculate heat release rate (HRR), mass burn fractions (MBF) as well as the combustion duration.

In-Cylinder Pressure and Heat Release Rate

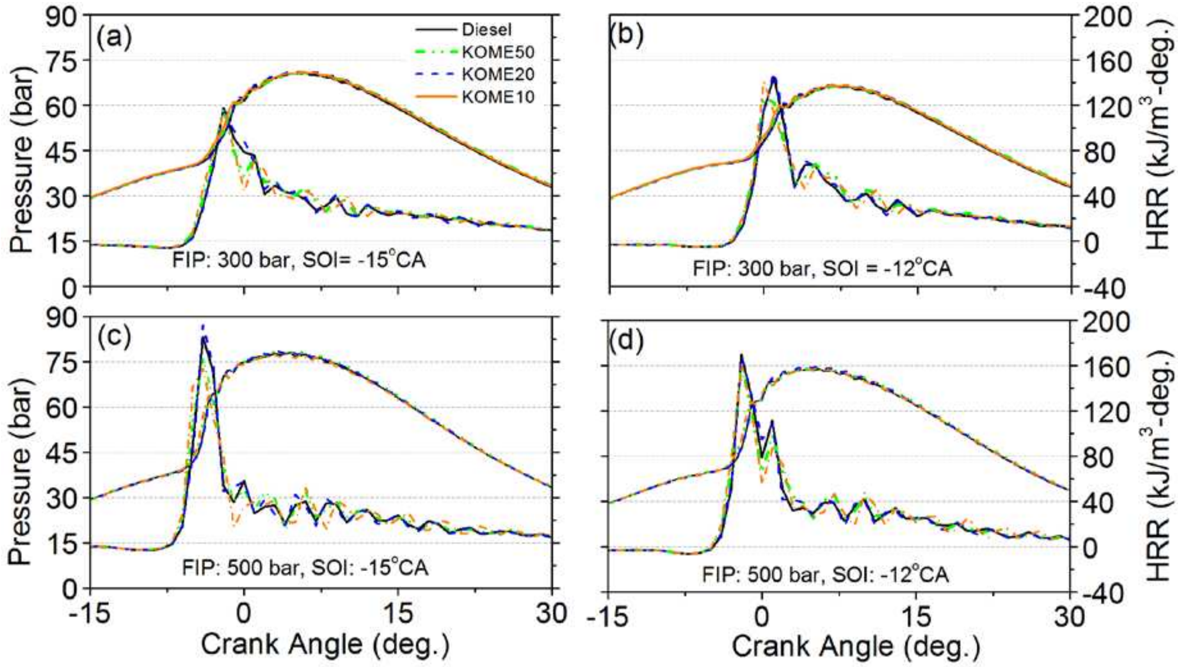


Figure 11: Variation of in-cylinder pressure and HRR with FIP and SOI at 300 and 500 bar FIPs

Figure 11 shows the variation of cylinder pressure and HRR at -15 and -12°CA SOI timings at 300 and 500 bar FIPs for Karanja biodiesel blends vis-à-vis mineral diesel. Negative heat release was observed for all test fuels due to cylinder charge cooling because of vaporization of the fuel accumulated during the ignition delay period. HRR becomes positive after the start of combustion (SOC). After the ignition delay, premixed air-fuel mixture burns rapidly, followed by diffusion combustion, when the HRR is controlled by rate of air-fuel mixing. Figure 12 shows the variation in in-cylinder pressure and HRR with SOI timings for higher injection pressures (750 and 1000 bar FIP) for Karanja biodiesel blends vis-a-vis mineral diesel. For all the test fuels, shift in in-cylinder pressure and HRR curves is consistent with shift in SOI timings.

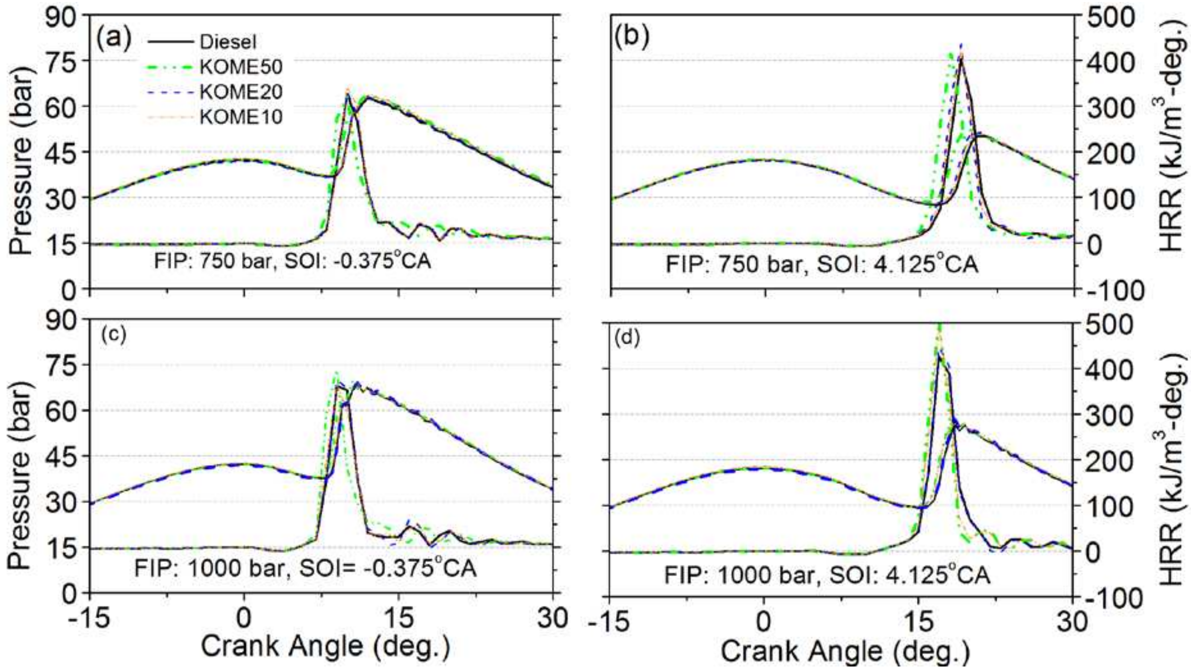


Figure 12: Variation of in-cylinder pressure and HRR with FIP and SOI at 750 and 1000 bar FIPs

Start of heat release was slightly advanced for KOME10 in comparison to other test fuels at 300 and 500 bar FIPs and this advancement was higher at advanced SOI timings (-15° CA SOI timing). Maximum premixed heat release for KOME20 was comparable to mineral diesel and maximum premixed heat release of KOME50 was slightly lower than mineral diesel. Reduction in heat release in premixed phase for biodiesel is also reported by other researchers [30-32]. This is mostly attributed to biodiesel's lower volatility in addition to the shorter ignition delay [30,32,33]. At higher FIP and advanced SOI timings (Figure 12), start of combustion advances for KOME50 in comparison to other fuels however at retarded injection timing (figure 12(d)), start of heat release for KOME50 was comparable to lower Karanja biodiesel blends and mineral diesel. Ye *et al.* also reported slightly advanced SOC for B40 in comparison to mineral diesel for SOI timings in the range of -9 to +3° crank angle for varying injection pressures [30]. Effect of lower volatility of biodiesel and almost comparable cetane number of Karanja biodiesel and mineral diesel may not be significant to alter the HRR profile of lower biodiesel blends in an engine equipped with CRDI fuel injection system.

Maximum Cylinder Pressure and its Location

Figure 13 shows the variation in maximum cylinder pressure and position of maximum pressure with SOI timing at 300, 500, 750 and 1000 bar FIPs. For all test fuels, maximum cylinder pressure decreased and position of maximum pressure retarded with retarding SOI timings at all FIPs. Retarded position of the peak cylinder pressure with retarding SOI timings increased the combustion chamber volume at the time of maximum pressure, which resulted in reduction of peak cylinder pressure for retarded SOI timings. At 300 bar FIP, maximum cylinder pressure for KOME20 was slightly higher than other fuels at advanced SOI timings (figure 13(a)).

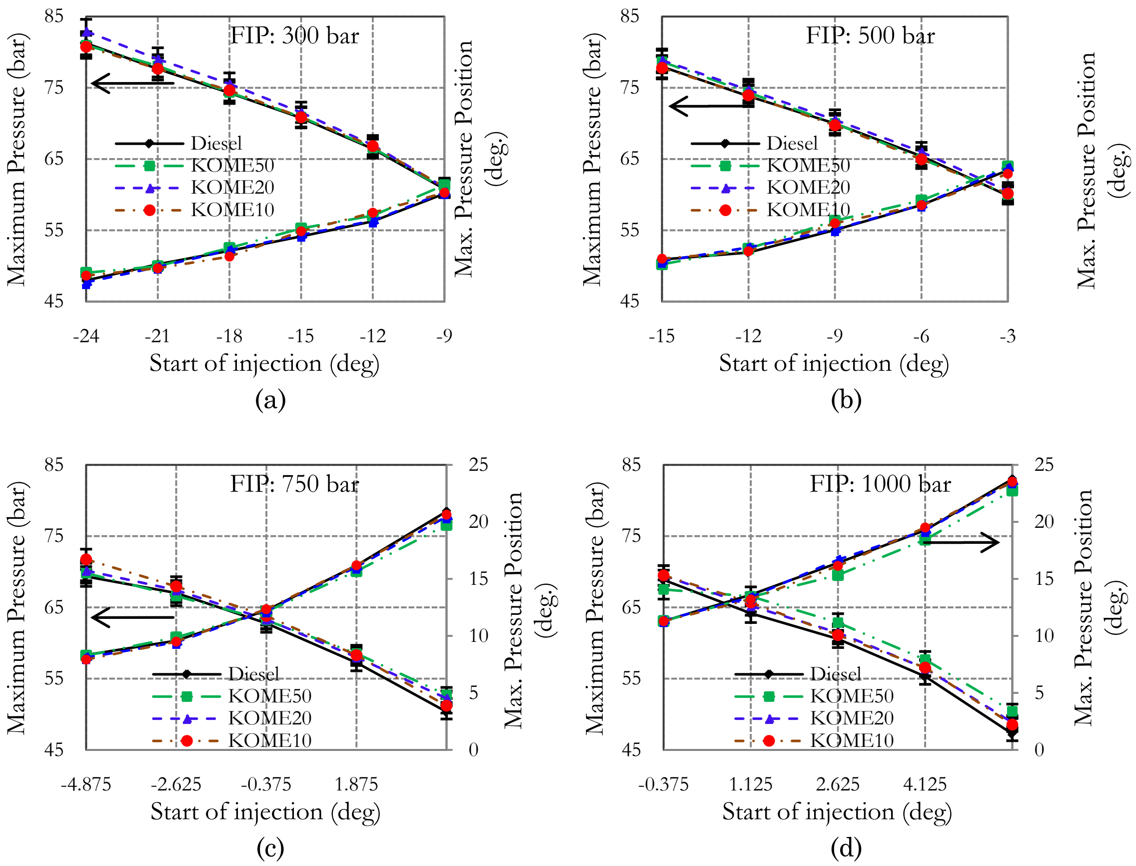


Figure 13: Variations in maximum cylinder pressure and its position vis-à-vis SOI timings for test fuels at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs

It can be explained by improvement in combustion due to oxygen content of biodiesel. With higher concentration of biodiesel in the test fuel, this improvement in combustion is offset by inferior spray atomization and poorer mixing characteristics caused by high fuel viscosity and inferior volatility of biodiesel. At retarded SOI timings, maximum in-cylinder pressures of all test fuels were almost same (figures 11). At retarded injection timings, cylinder temperature and pressure were comparatively higher during fuel injection, which improves spray characteristics and reduces the ignition delay for all test fuels, thus reducing the difference in the combustion characteristics of different test fuels. At 750 and 1000 bar FIPs, maximum cylinder pressure of biodiesel increases with increasing biodiesel concentration in the blend at retarded injection timings. At advanced injection timings, maximum cylinder pressure of higher biodiesel blends was comparatively lower (figures 12 (c)-(d)). It shows that higher cylinder pressures and temperatures during the injection improve the spray characteristics of higher viscosity and low volatility fuels. Maximum cylinder pressure increased with increasing FIP at fixed SOI timings for all test fuels due to increased HRR because of improved fuel-air mixing. Suh et al. also observed increased combustion pressure and heat release rate for rapeseed biodiesel blends, when injection pressure were increased to 1000 bar. They concluded that higher fuel injection pressure cause better fuel injection and atomization of higher viscosity biodiesel [10].

Start and End of Combustion

SOC is characterized by position of 10% MBF in terms of crank angle degree. End of combustion (EOC) is characterized by position of 90% MBF. Figure 14 shows the variations in start and end of combustion with varying SOI timings at 300, 500, 750 and 1000 bar FIPs.

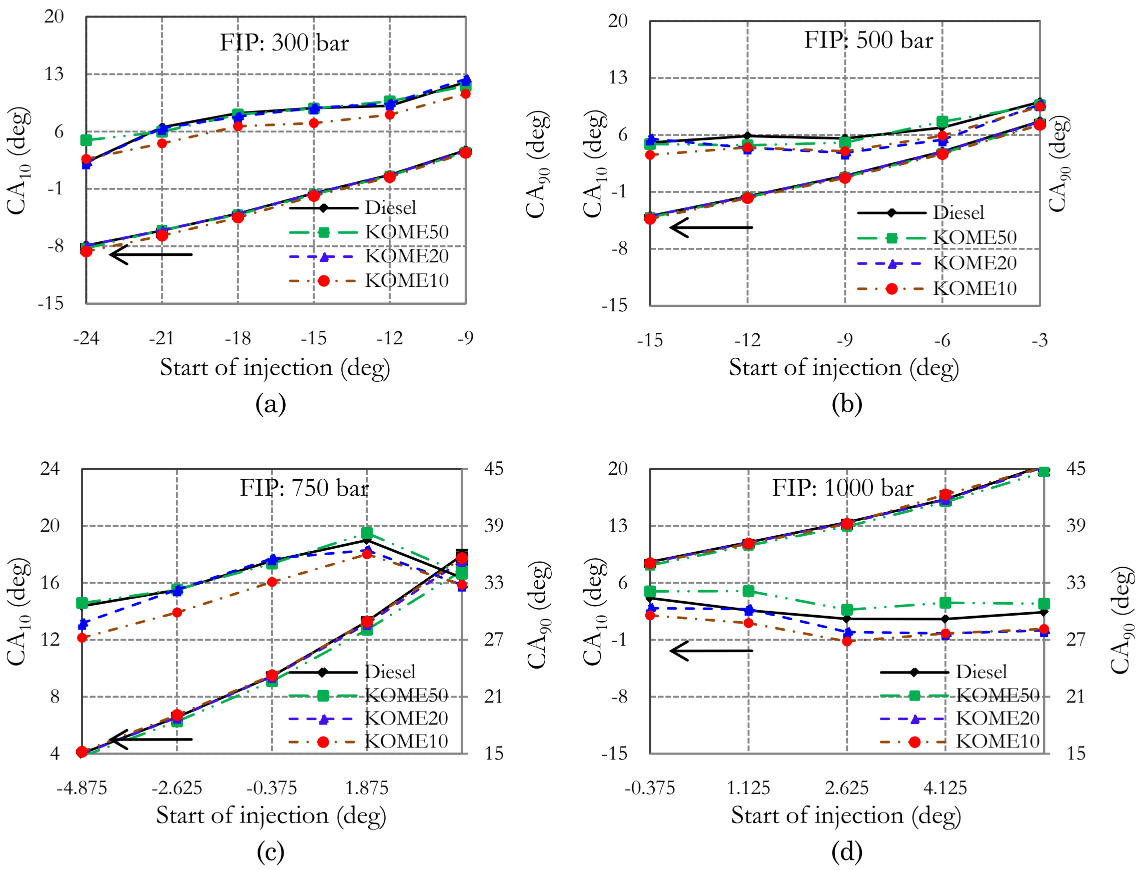


Figure 14. Variations in position of 10% and 90% MBF position vis-à-vis SOI timings for test fuels at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIP

At 300 and 500 bar FIPs, 10% MBF position was almost identical for all test fuels (Figures 14(a)-(b)). At higher FIPs, SOC was slightly advanced for KOME50 in comparison to other fuels at all SOI timings (Figures 14(c)-(d)). KOME10 and KOME20 showed earlier EOC in comparison to mineral diesel for all SOI timings. 90% MBF position of KOME50 was delayed in comparison to mineral diesel and this delay increased with increasing FIP. It shows that increasing FIP was relatively more effective in improving the atomization characteristics and mixing of mineral diesel and lower biodiesel blends. At same SOI timings, SOC advanced with increasing FIP for all test fuels.

Combustion Duration

Combustion duration is the difference between 90% and 10% MBF positions in terms of crank angle degrees. Figure 15shows the variation in combustion duration with SOI timings at 300, 500, 750 and 1000 bar FIPs. It can be observed that combustion duration decreased with retarding SOI timings for all test fuels at all FIPs. Retarded SOI timings delayed both start and end of combustion (Figure 14) but delay in SOC timing was longer in comparison to EOC timing. This longer delay in SOC timing resulted in shortening of combustion duration with retarded SOI timings. Combustion duration of KOME10 and KOME20 was shorter than mineral diesel. Combustion duration of KOME50 was comparable to mineral diesel at 300, 500 and 750 bar FIPs. At 1000 FIP, combustion duration of KOME50 was higher than mineral diesel.

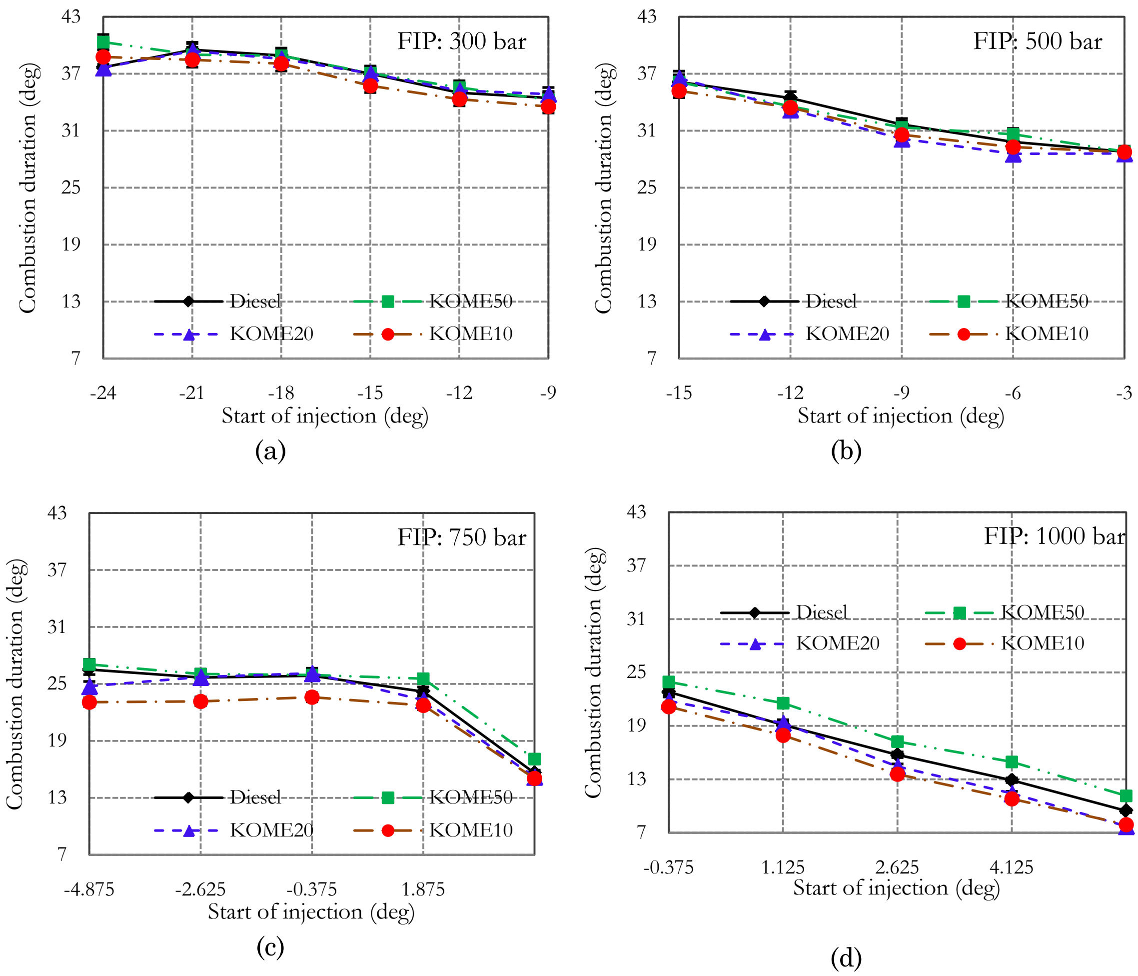


Figure 15. Variations in combustion duration vis-à-vis SOI timings for test fuels at (a) 300, (b) 500, (c) 750 and (d) 1000 bar FIPs

Combustion duration decreased with increasing FIP for all test fuels. Lower biodiesel blends showed faster HRR in comparison to mineral diesel due to fuel oxygen, which also resulted in shorter combustion duration. Higher concentration of biodiesel in test fuels resulted in inferior atomization and fuel-air mixing characteristics due to higher fuel viscosity and inferior volatility characteristics of biodiesel vis-a-vis mineral diesel, which in-turn increased combustion duration of biodiesel blends in the CRDI engine. Similar results of increased combustion duration with increasing biodiesel blend ratio were also observed by CAN. They attributed this behaviour to higher fuel injection duration and slower combustion rate [14].

4. Conclusions

Effects of fuel injection pressure and start of injection timings on CRDI engine performance, emissions and combustion characteristics of Karanja biodiesel (KOME) blends and baseline mineral diesel were investigated at a constant engine speed of 1500 rpm, in addition to comprehensive spray investigations were carried out. The fuel injection duration decreased slightly with increasing biodiesel content in the biodiesel blend. Fuel injection duration shortened and peak injection rate increased with increasing fuel injection pressure. Sauter mean diameter and arithmetic mean diameter of fuel spray droplet (D_{32} and D_{10}) decreased with reduction in biodiesel blending ratio due to relatively lower fuel density and viscosity.

Brake thermal efficiency of biodiesel blends was slightly higher than mineral diesel. Increasing fuel injection pressures generally improved the thermal efficiency of test fuels. SOI timing corresponding to maximum thermal efficiency was identical for biodiesel blends and mineral diesel. Lower biodiesel blends showed lower BSCO and BSHC emissions in comparison to mineral diesel however BSHC and BSCO emissions were found to be higher for some operating conditions for KOME50. BSNOx emissions for KOME20 were higher than mineral diesel however they were almost identical to mineral diesel for other blends. Maximum cylinder pressure increased with increasing fuel injection pressure at fixed SOI timing for all test fuels and SOC advanced for lower biodiesel blends in comparison to mineral diesel. For lower biodiesel blends, combustion duration was relatively shorter than mineral diesel but at higher FIPs, combustion duration of KOME50 was found to be relatively longer. These experimental results showed that utilization of upto 10% Karanja biodiesel blends in a CRDI engines can be done for improving engine efficiency and reducing emissions, without any significant hardware changes or ECU recalibration.

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