Applied Energy 130 (2014) 212–221

Contents lists available at ScienceDirect

Applied Energy

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

# Effect of fuel injection pressure and injection timing on spray characteristics and particulate size–number distribution in a biodiesel fuelled common rail direct injection diesel engine

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## HIGHLIGHTS

- Effect of injection pressure on spray characteristics of biodiesel blends and diesel.
- Effect of injection pressure and SOI timing on particulate emissions.
- Spray tip penetration was longer at higher fuel injection pressures.
- Particulate size increased with retarding SOI timings.
- Particulate number concentration was lowest for KOME10.

## ARTICLE INFO

*Article history:*
Received 25 November 2013
Received in revised form 19 April 2014
Accepted 20 May 2014

*Keywords:*
Spray characteristics
Particulate
Size number distribution
Karanja biodiesel
Fuel injection timing
Fuel injection pressure

## ABSTRACT

In this paper, effect of varying fuel injection pressures and injection timings on particulate size number distribution and spray characteristics was investigated in a single cylinder, common rail direct injection (CRDI) compression ignition (CI) engine fueled with Karanja biodiesel blends vis-à-vis baseline mineral diesel. The investigation results of spray tip penetration and spray area of biodiesel blends and diesel showed that higher fuel injection pressure result in a longer spray tip penetration and larger spray area than that at lower injection pressures at same elapsed time after the start of injection (SOI). In order to compare the effect of fuel injection parameters, 10, 20 and 50% Karanja biodiesel blends at 1500 rpm engine speed were compared with baseline data from mineral diesel. It was observed that average particulate size increased with retarding the SOI timings. Particulate number concentration was lowest for 10% biodiesel blend, which increased with further increase in biodiesel content in the blended test fuel. Addition of even very small quantity of biodiesel in the test fuel helped in reducing particulate emissions.



## 1. Introduction

Major pollutants of concern emitted by compression ignition (CI) engine are oxides of nitrogen ($NO_x$) and particulate matter (PM). Trade-off between them and the ever plunging limits of these pollutants enforced by new emissions legislations pose huge challenges in development of engines and alternative fuels. For controlling emissions, higher fuel injection pressures, split and multiple injections, exhaust gas recirculation (EGR), intake air pressure boosting etc. are being applied. Biodiesel produced from different feedstocks is being considered as an alternative fuel for mineral diesel in various countries in order to ensure energy security in prevailing situation of scarcity of petroleum based fuels. Considering a strong correlation between the toxicity of particulates with their size and number concentrations, newer emission legislations have started to enforce limits on the number of particulates emitted in addition to particulate mass emissions [1–5]. Therefore it is important to investigate the effect of various fuel injection strategies and newer fuels on particulate number emissions.

Desantes et al. investigated the effect of fuel injection pressure, start of injection (SOI) timings and exhaust gas recirculation (EGR) on size distribution of exhaust particles emitted by a heavy duty

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http://dx.doi.org/10.1016/j.apenergy.2014.05.041
0306-2619/

diesel engine [6]. Increasing fuel injection pressure was found effective in reducing the accumulation mode particle numbers and it favored formation of nuclei mode particles. For diesel, Puzun et al. reported that particle number concentrations showed single peak distribution curves with dominating accumulation mode particles [7]. For biodiesel blends, authors reported that at low and medium load conditions, with increasing concentration of biodiesel in the fuel, particle size distributions changed from single peak to a double peak distribution [7]. Kousoulidou et al. [8] reported 24% and 17% reduction in particulate emissions for 10% rapeseed biodiesel and Palm biodiesel blend fuelled engines respectively in comparison to baseline mineral diesel. Ye and Boehman concluded that the impact of injection strategy and biodiesel fueling on particulate emissions strongly depends on the engine load in a common rail direct injection (CRDI) engine. At low load conditions, increase in fuel injection pressure and biodiesel fueling can significantly reduce particulate emissions. However, at moderate to high loads, biodiesel fueling has less significant impact on particulate emissions [9]. Yamane et al. observed that particulate emissions for biodiesel showed a higher level at lower engine loads, primarily due to higher soluble organic fraction (SOF) content of the particulates [10]. Kim et al. reported that biodiesel shifted the particulate size distribution towards smaller particulate diameters [11].

In modern CI engines, CRDI technology, which is highly flexible in terms of fuel injection strategies and employs high injection pressures (upto 1600 bar), is widely used. In this injection system, fuel injection pressure can be regulated by controlling the fuel rail pressure. Giakoumis conducted statistical investigations by deriving best-fit quadratic regression curves, collected results and statistical data to quantify the effects of biodiesel blending on regulated emissions. Despite the highly scattered data, a rather compelling decreasing trend for PM, CO and HC emissions was observed and similar best-fit approximations were obtained for a more realistic scenario of biodiesel blends up to 50% [12]. Studies discussed above show that there are several studies related to particulate and spray characteristics on different biodiesels however there are very few studies which explain the effect of fuel injection pressure and injection timings on the particulate size–number distribution and spray characteristics of diesel and biodiesel fueled engines. Due to shortage of edible oils in India, biodiesel policy of Indian government recommends utilization of non-edible oils for biodiesel production [13]. Karanja oil is one of the major non-edible, tree-borne feedstock for producing biodiesel in India and south Asia on a large scale because it is well adapted to local climatic conditions and is available in surplus quantities all over the region [14].

Therefore, in this research, the effect of biodiesel blends on macroscopic spray characteristics, varying fuel injection pressures and SOI timings on the particulate size–number distribution was experimentally investigated on a single cylinder CI engine equipped with high-pressure common rail direct injection system fueled with Karanja biodiesel blends vis-à-vis baseline mineral diesel. For investigating the effect of fuel injection timings and fuel injection pressures on particulate number emissions, engine operating point corresponding to approximately 5 bar BMEP (AFR 23 for diesel) at medium speed (1500 rpm) was selected. During actual operation, engine operates in the vicinity of this operating point most of the time. Hence, it was selected as a representative operating point and variation of SOI timing and fuel injection pressure was studied at this operating point.

## 2. Experimental setup and procedure

Schematics of experimental setups used, in which experimental investigations of particulate size–number distribution and spray characteristics of Karanja biodiesel and diesel were performed, are shown in Fig. 1. Effect of varying fuel injection pressure (FIP) and SOI timing on particulate size–number distribution was investigated in a single cylinder engine (AVL List GmbH, 5402) equipped with an AC (transient) dynamometer. It is equipped with a CRDI fuel injection system. This test engine is capable of varying and having desired setting for fuel injection pressure, injection timing and injected fuel quantity. Particulate size–number distribution characterization was performed at 300, 500, 750 and 1000 bar FIPs with varying SOI timings. During the experiments, temperature of fuel was maintained at 20°C using a fuel conditioning unit (AVL List GmbH, 753CH). Temperature of the coolant was kept constant at 80°C by coolant conditioning unit (Yantrashilpa, YS4027). Temperature and pressure of lubricating oil was maintained at 90°C and 3.5 bar, respectively, by using an oil conditioning unit (Yantrashilpa, YS4312). Particulate size–number distribution was measured by Engine Exhaust Particle Sizer™ (EEPS) (TSI Inc., 3090). It can measure particle sizes in the range of 5.6–560 nm up to a maximum concentration of $10^8$ particles/$cm^3$. EEPS performs the classification of particle sizes based on the differences in individual particle's electrical mobility diameter [15]. In current investigations, engine exhaust was diluted using a rotating disk thermo-diluter (Matter Engineering AG, MD19-2E) before supplying the exhaust gas sample to the EEPS for particulate size–number distribution measurements. Particle size–number distribution in the engine exhaust was finally calculated by multiplying the particulate size-number distribution of the diluted exhaust with the dilution factor. After the thermal stabilization of the engine, particle size–number distribution data was recorded for 60 s at a frequency of 1 Hz. Data presented in the next section is an average of 60 successive measurements and the error bars correspond to the standard deviation in the measurement.

The spray visualization system, which is used to measure the macroscopic spray characteristics of Karanja biodiesel and mineral diesel, consists of a high-speed camera (Photron, Fastcam-APXRS), a metal-halide lamp (Photron, HVC-SL), an electronic synchronization system between the fuel injector, and the image acquisition system (camera) as shown in Fig. 1(a). The fuel injection and spray system comprise of a common-rail type high-pressure injection pump (Haskel, HSF-300), an injector driver (TEMS, TDA-3200H), an electronically controlled injector with six holes, a digital delay generator (Berkeley Nucleonics Corp, 555), a high-pressure visualization chamber with optical windows, in which ambient pressure was varied using pressurized Nitrogen, and a data acquisition system with image grabber. Injector used in this experiment was controlled by an injector driver, and Karanja biodiesel and blends were supplied to a multi-hole injector through the high-pressure fuel injection pump and the common rail. The control signals of the fuel injection and shutter of a high-speed camera were synchronized using a digital delay and pulse generator. In this measurement, shutter speed of high-speed camera was set at 10,000 fps. The macroscopic spray characteristics were measured using a visualization system and a pressurized spray chamber with optical windows.

Particulate size–number characteristics of 10%, 20% and 50% Karanja biodiesel blends (KOME10, KOME20, KOME50) at constant engine speed (1500 rpm) were compared with baseline mineral diesel. Important physical properties of test fuels used in this investigation are given in Table 1.

Cetane numbers of Karanja biodiesel (KOME100) and mineral diesel used in this study were 50.8 and 51.2 respectively. Fuel energy input to the engine was kept constant for all engine operating conditions and it was equivalent to an air–fuel ratio (AFR) of 23 for mineral diesel. Engine operating point corresponding to approximately 5 bar brake mean effective pressure (BMEP) engine load and 1500 rpm engine speed was selected for detailed investigations for evaluating the effect of FIP and SOI timings on particulate size–number distribution.