COMPARATIVE STUDY OF MACROSCOPIC SPRAY PARAMETERS AND FUEL ATOMIZATION BEHAVIOUR OF STRAIGHT VEGETABLE OILS (JATROPHA), ITS BIODIESEL AND BLENDS

by

Avinash K. AGARWAL**, *Vipul CHAUDHURY, Anuj AGARWAL, and Pravesh C. SHUKLA

Engine Research Laboratory, Department of Mechanical Engineering,
Indian Institute of Technology Kanpur, India

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The combustion and emission characteristics of vegetable oils and derivatives are quite different from mineral diesel due to their relatively high viscosity, density, and vaporisation characteristics. These properties affect the fuel spray and the interaction of the spray with air in the combustion chamber therefore it is important to analyse the spray characteristics e. g. spray tip penetration, spray cone angle, spray area, and fuel atomization. Optical techniques for spray visualization and image processing are very efficient to analyse the comparative spray parameters for these fuels. Present research investigates the effect of chamber pressure on spray characteristics of jatropha straight vegetable oils (J100) – blends (J5, J20), and jatropha biodiesel (JB100) – blends (JB5, JB20) vis-à-vis baseline data of mineral diesel. Experiments were performed for all these fuels/ blends injected in a constant volume spray visualisation chamber (cold chamber) at four different chamber pressure (1, 4, 7, and 9 bar, respectively). It was found that J100 and JB100 have the highest spray tip penetration, cone angle, and the spray area followed by J20, J5, mineral diesel and JB20, JB5, mineral diesel, respectively, however J20, J5 and JB20, JB5 have better atomization characteristics as compared to J100 and JB100, respectively. Cone angle was higher for biodiesel blends as compared to straight vegetable oils blends at atmospheric pressure however as the chamber pressure was increased to 9 bar, it became almost equal for both fuel types. Spray parameters are found to be excellent for mineral diesel followed by jatropha biodiesel and jatropha oil. It was found that atomization of fuel becomes superior with increasing chamber pressure.

Key words: *jatropha oil, spray characterisation, spray tip penetration, spray cone angle, spray area, fuel atomization*

Introduction

Petroleum based conventional fuels used in internal combustion engines lead to significant environmental problems and this resource is depleting rapidly. Diesel engines form the backbone of surface transportation today. Diesel engines are preferred over their gasoline counterparts because of higher thermal efficiency and durability. Fuel used in these engines is primarily mineral diesel. Fossil petroleum fuels have limited reserves and are depleting rapidly. There is a need to find alternative ways to fulfil the galloping requirement of transportation fuels. In the recent past, many researchers have attempted to develop alternative fuels for diesel

* Corresponding author; e-mail: akag@iitk.ac.in

engines, especially from bio-origin. One of the important characteristics of biofuels is that they have different fuel properties vis-à-vis mineral diesel. Because of different properties, biofuels have different spray behaviour and fuel atomization characteristics compared to mineral diesel [1]. This is the main reason to investigate the spray behaviour and fuel droplet atomization parameters for biofuels. For the developing countries, biofuels will play an important role in fulfilling their energy requirements in near future. These biofuels include alcohols, biomass, biogas, biodiesel, *etc*.

Jatropha seeds are one of the important sources of jatropha oil, which can be used for making biofuels, more specifically biodiesel, a potential alternative diesel engine fuel [2]. Jatropha has emerged as an efficient and sustainable candidate fuel resource for diesel engines and it is a promising candidate for lowering the emissions [3]. Using straight vegetable oils (SVO) in the engine is quite difficult because of their vastly different properties compared to mineral diesel. For making them suitable for use in engines, transesterification is required for converting them into biodiesel. Biodiesel is therefore an oxygenated fuel containing mono-alkyl ester derived from transesterification of SVO – waste cooking oil and animal fat. Biodiesel is degradable, nontoxic and environmental friendly fuel [4, 5]. Kuthalingam *et al*. [2] investigated the performance and emission characteristics of biodiesel prepared with the mixture of two different origins for use in diesel engines. They used two different biodiesel blends: (1) pongamia pinnata biodiesel, and mustard oil biodiesel blended with mineral diesel (PMD) and (2) combinations of cotton seed biodiesel, and pongamia pinnata biodiesel blended with mineral diesel (CPD). They found that the CPD blend gives superior engine characteristics, which indicate that this is a good alternative for mineral diesel.

Soid and Zainal [6] reviewed several research papers in the field of spray characterization and combustion behaviour and presented the importance of the spray and combustion investigations using optical techniques. Banhawy and Whitelaw [7] investigated the spray behaviour and combustion in ambient air at different degrees of swirl. Kortas *et al.* [8] studied diesel spray development experimentally. In their experiment, they observed the spray 0.5 ms after the start of injection using an ultra-high speed camera. Klein-Douwel *et al.* [9] attempted to understand the interaction of fuel injection and spray propagation by using high speed imaging in a high pressure cell. They explained the procedure to determine the local spray angle, cone angle, and spray penetration. They also explained the experiment and algorithm for geometric analysis. Fang and Lee [10] investigated spray and combustion development and the influence of different injection strategies using biodiesel blends in an optical engine. They used European low sulphur diesel (B0), soybean biodiesel blends (B20, B50), and pure soybean biodiesel (B100) with three different injection timings for their study. Combustion visualization showed that fuel blends with higher biodiesel content had longer spray tip penetration and higher fuel impingement.

Jatropha oil is a non-edible oil derived from *J. Curcas* plant [11]. This plant can survive in adverse condition, and requires very little water for irrigation and can grow in any type of soil. Dedicated jatropha plantation can give a seed yield of 0.8 kg/ m^2. Jatropha seeds contain approximately 30-40% oil (w/w) and it is odourless, colourless, and slow-drying oil [12, 13]. The main issue with jatropha is that its seeds are toxic and the press cake (after extracting the oil) can not be used as animal feed. Jatropha oil can not be used for any nutritional purpose without removing its toxic contents, therefore it a good alternate fuel candidate. Pramanik [12] also explored jatropha as an alternate diesel engine fuel by reducing its viscosity using preheating of oil.

In the present study, jatropha SVO, jatropha biodiesel and their blends with mineral diesel were chosen for comparison of their spray characteristics vis-à-vis baseline mineral diesel. Spray characterization study includes spray tip penetration, spray cone angle, and spray area. Spray tip penetration is the length of the spray between the injector hole and the tip of spray [14, 15]. Spray cone angle is defined as the angle between two lines connecting the nozzle tip and the two "half penetration points" on the spray boundary. Spray area is defined as an area covered by the fuel spray in the combustion chamber at chamber pressure-temperature conditions.

Experimental set-up

Figure 1 shows the experimental set-up for investigating the macroscopic spray parameters. It includes a constant volume spray chamber, air compressor, fuel injection system, high speed imaging system, and a data acquisition system. Constant volume spray chamber has been pressurised and tested upto an ambient air pressure of 10 bar, without any failure. The spray visualization chamber has four optical windows, 16 cm diameter each. The lower portion of the chamber is conical and its apex is connected to a drain valve. Drain valve is used for removing the fuel, when the chamber accumulates some quantity of liquid fuel during the experiment. Fuel injector and the pressure gauge are mounted on top of the chamber. Air supply line is connected to the spray chamber for maintaining the required chamber pressure. Optical windows are made from toughened glass (19 mm thickness) and it is able of withstanding 10 bar pressure. A reciprocating air compressor (Vayu Air Compressor, India, model SA10081R) is used for supplying pressurised air and maintaining required chamber pressure (maximum 10 bar). The fuel injection system used in the spray experiments is identical to the one used in a production grade constant-speed single-cylinder genset engine (Kirloskar oil Engines Limited, Pune, India; model DM-10). The injector is a simple mechanical fuel injector with delivery valve

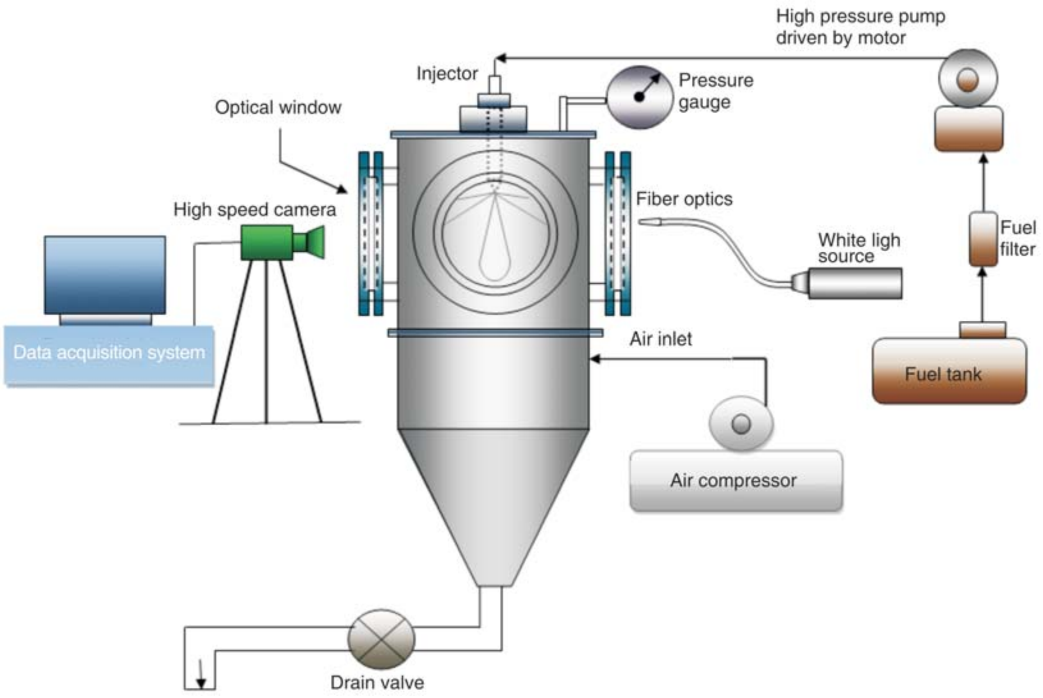

Figure 1. Schematic of the experimental set-up for fuel spray characterisation

opening pressure set at 200 bar. It has three nozzles (diameter = 290 μm), which are at 120° angle mutually. Mechanical jerk pump delivers fuel at 200 bar. Fuel injector is connected to the fuel pump via a high pressure line and fuel pump is operated using an electric drive (0.5 hp) for the present experiment. A white light source (Thorlabs, USA, model High Intensity Fiber Light Source OSL1) is used to illuminate the spray droplets in the chamber. Illuminated fuel droplets are visualized from the other window, located orthogonally using a high speed camera (Basler; model, A601fc). The high speed camera is connected to the data acquisition system and images are captured using image grabbing and analysis software. A kinematic viscometer (Stanhope Seta, UK, model Setavis 11300) is used for measuring the viscosity of jatropha oil blends, and biodiesel blends vis-à-vis mineral diesel. A portable density meter (Kyoto Instruments, Japan, model DA-130N) was used for measuring density of the test fuels.

Experimental matrix

The experiments were carried out at 200 bar fuel injection pressure for mineral diesel, jatropha oil, jatropha biodiesel and their blends with mineral diesel (J5, J20, J100, JB5, JB20, and JB100). Before starting the experiment, leak test was performed on the spray chamber. The chamber pressure was maintained at 10 bar and it was found to be stable and leak proof. Experiments were performed for four different chamber pressures (9, 7, 4, and 1 bar). Viscosity and density of test fuels are critical parameters in spray characterization, therefore these properties were measured experimentally.

The image grabbing software communicates with the high speed camera. The best image from the several images captured by the camera was chosen and analysed for the macro-analysis of spray characteristics using the software (National Instrument's Vision Assistance, 2009). The software has a graphical tool to process the images effectively. This software analyzes the image according to the number of pixels and pixel values (pixel intensity). The brightness level and the threshold values were fixed for image analysis for all the experiments. Each of the experiment has been performed three times and average has been taken. It has been calculated that accuracy lies within ±3% for all test results. It was found that the third image in the injection sequence (from the start of injection, taken after 50 ms) is the best picture giving necessary details. This image taken 50 ms after the start of injection is chosen to be analysed for all the experiments and all test fuels.

Results

The aim of the present study is to investigate the spray characteristics and fuel droplet atomization behaviour of the test fuels. Viscosity and density of the test fuels vis-à-vis mineral diesel have been determined. Kinematic viscosity of jatropha SVO is 38.84 cSt at 40 ºC, which is an order of magnitude higher than mineral diesel and the density is 918 kg/m^3 at 15 ºC, which is also higher than mineral diesel. Table 1 shows the measured fuel properties (density and kinematic viscosity) of these tests fuels (biodiesel and blends).

Table 1 shows that mineral diesel has lower density and kinematic viscosity compared to jatropha SVO and biodiesel. Fuels with higher density exhibit inferior spray and atomization characteristics. When fuel injection starts, droplets move fast and tend to break in to smaller droplets. The droplet size distribution depends on the density of the fuel to a large extent. If test fuel has lower density, atomization takes place quickly and in case of higher density fuels (such as SVO), it takes longer time to atomize (because of their higher intra-molecular forces, called van-der-Waals forces). This atomization phenomenon happens in milliseconds after the start of injection. Fuels with higher density leads to higher spray tip penetration and poor atomization because of their higher intra-molecular forces. This leads to formation of larger fuel droplets, which have relatively higher inertia and therefore they travel longer distances in the spray chamber. jatropha SVO has the highest density among the test fuels followed by jatropha biodiesel and mineral diesel. Higher spray jet penetration and poor atomization behaviour of fuels may cause inefficient fuel- air mixing, and may consequently lead to formation of higher soot in the engine. In this study, the objective of the work is to characterize the spray and spray atomization behaviour investigations for the test fuels in question (mineral diesel, jatropha SVO, jatropha biodiesel and their blends).

Table 1. Kinematics viscosity and density of the test fuels

Fuels	Density [kgm^{-3}] at 15 ºC	Kinematic viscosity (cSt) at 40 ºC
Diesel	817	2.55
J5	826	3.86
J20	838	4.66
J100	918	38.84
JB5	820	2.96
JB20	829	3.1
JB100	882	5.27

Spray characterization

Fuel spray characterization investigations in this study include (1) spray tip penetration, (2) spray cone angle, and (3) spray area.

Spray tip penetration

Spray tip penetration has been analyzed for all the test fuels and are shown in fig. 2. Spray tip penetration is the maximum length attained by the spray tip during the injection process. Fuel injection pressure was kept constant at 200 bar for each test case.

The spray tip penetration decreases as chamber pressure increases for all test fuels (fig. 2). The chamber pressure rise (from 1 to 9 bar) increases the air density inside the chamber. Fuel droplets at the spray tip face higher shear resistance from the denser air present in the chamber. Due to this, the droplet velocity, which is very high initially, decreases slowly at the tip of the

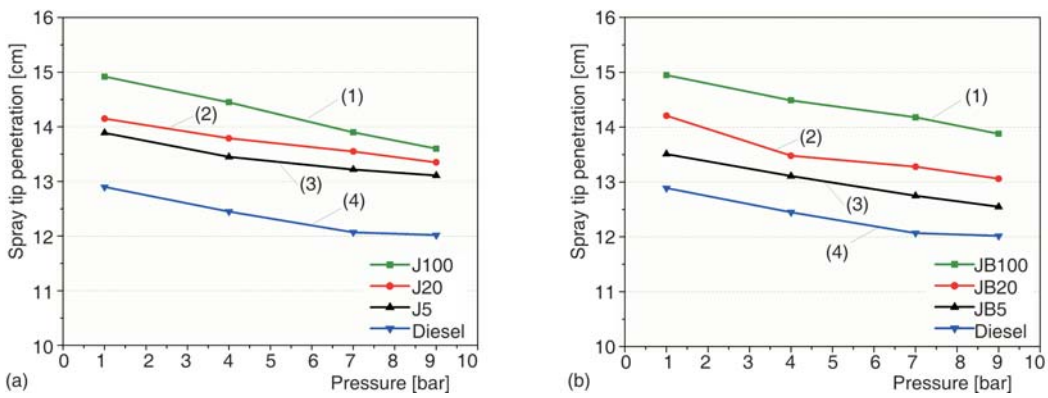

Figure 2. Spray tip penetration of (a) jatropha blends and (b) jatropha biodiesel blends at various chamber pressures 50 ms after the start of fuel injection

spray. This leads to reduction in spray tip penetration with increasing chamber pressure. It can be seen from fig. 2 that the spray penetration of mineral diesel is lowest for all chamber pressures because the density and viscosity of mineral diesel is lowest among all test fuels and it atomizes most rapidly amongst all test fuels. jatropha oil (J100) has the highest spray tip penetration at 1, 4, 7, and 9 bar chamber pressures followed by J20, J5, and mineral diesel, fig. 2(a). Jatropha biodiesel (JB100) also shows highest spray tip penetration at 1, 4, 7, and 9 bar chamber pressure followed by JB20, JB5, and mineral diesel, fig. 2(b). Higher penetration of the spray tip increases the possibility of fuel jet hitting the cylinder walls and washing away the lubricating oil present on the surface to prevent the ring-liner interaction. Such fuel washing of the lubricating oil layer from cylinder walls increases the engine wear significantly and is therefore completely undesirable.

Roisman *et al*. [16] 2007 determined the maximum spray-tip velocity as a function of the ambient pressure for various injection pressures. It has been shown that the spray tip velocity decreases with increasing ambient pressure. In the present study, similar results have been obtained for spray tip penetration length, fig. 2. Spray tip penetration length decreases with increasing ambient pressure because of increased air resistance.

Spray cone angle

The spray cone angle was found by connecting the two points at half of the spray length from the nozzle, where pixel intensity is slightly higher than the critical pixel intensity. Images are analysed and results of cone angle is plotted for all test fuels in fig. 3.

In the experiment, it is found that the spray cone angle increases with increasing chamber pressure for all test fuels. SVO has higher fuel density compared to blends and biodiesel, therefore the SVO fuel droplets movement in radial direction is lower compared to its blends. However as the spray chamber pressure increases (from 1 to 9 bar), the fuel droplet concentration level increases at the bottom part of the spray because of higher ambient air resistance due to high pressure dense air in the spray chamber. This is the reason why the spray spreads radially and the cone angle increases with increasing spray chamber pressure, figs. 3 and 4. At 1 bar chamber pressure, J100, J20 and J5 had spray cone angles of 12.59º, 12.5º, and 11.53º, respectively, fig. 3(a). The spray cone angle for jatropha oil blends (J100, J20, and J5, fig. 3(a), is however lower than JB100, JB20 and JB5 (14.74º, 13.12º, and 12.73º, respectively) at 1 bar chamber

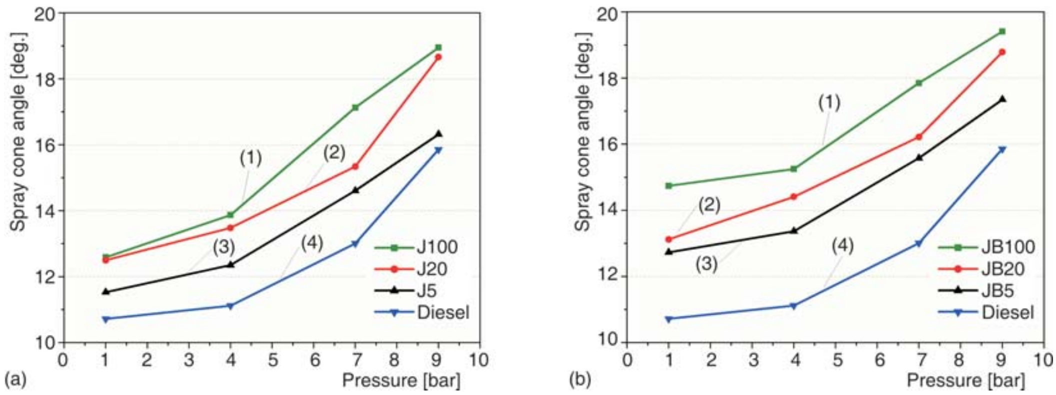

Figure 3. Spray cone angle of (a) jatropha blends and (b) jatropha biodiesel blends at various chamber pressures 50 ms after the start of fuel injection

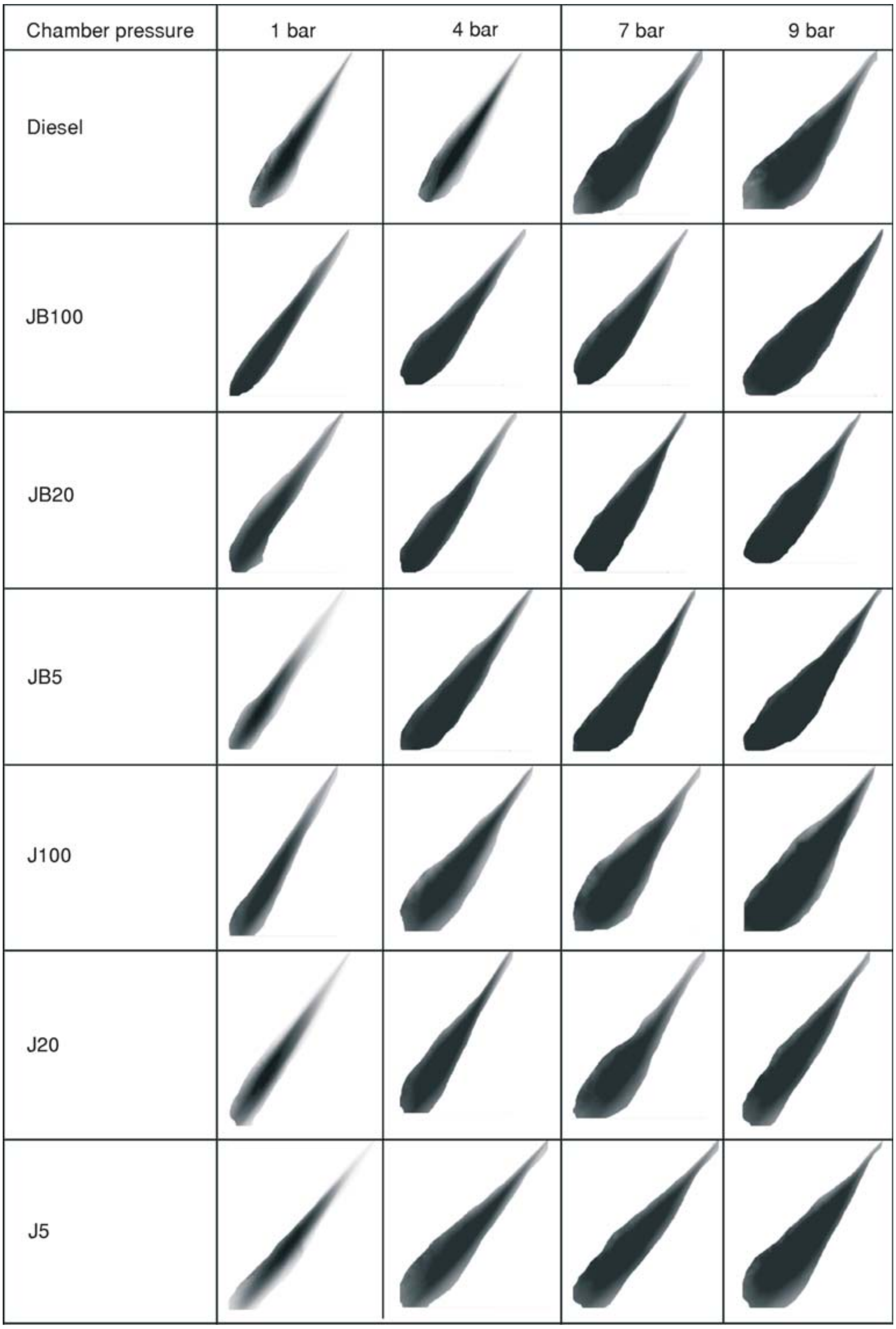

Figure 4. Effect of chamber pressure on fuel spray of test fuels 50 ms after start of fuel injection

pressure, fig. 3(b). As the chamber pressure increase to 9 bar, similar trends of spray cone angles for jatropha oil blends (J100, J20 and J5) and jatropha biodiesel blends (JB100, JB20, and JB5) vis-à-vis mineral diesel is observed. Figure 4 shows spray images for different test fuels at different chamber pressure for a comparative assessment (not to the scale).

Spray area

Spray area is the area covered by the fuel spray in the chamber at a given chamber pressure-temperature condition. The spray areas for all test fuels at various ambient pressures are shown in fig. 5.

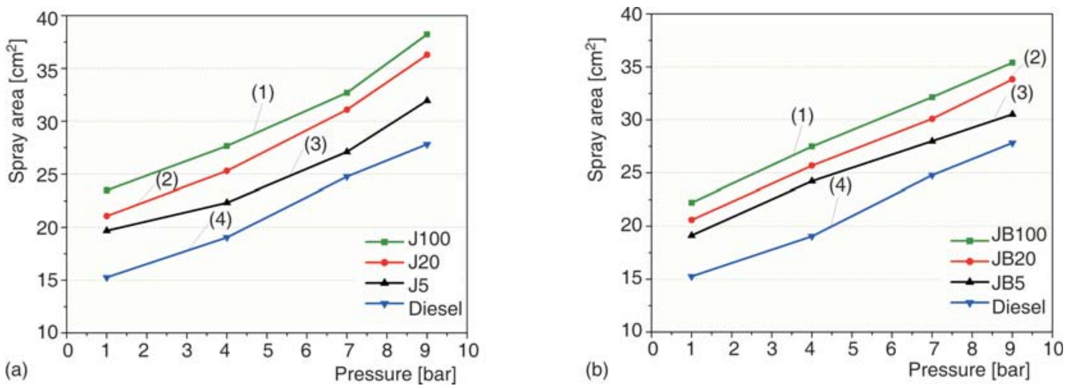

Figure 5. Spray area of (a) jatropha blends and (b) jatropha biodiesel blends at various chamber pressures 50 ms after the start of fuel injection

It is evident from fig. 5 that the spray area shows an increasing trend with increasing chamber pressure for all test fuels. Mineral diesel shows smallest spray area amongst all test fuels. The reason for this trend is same as explained for the spray cone angle. At all chamber pressures, the spray area is higher for jatropha blends, fig. 5(a), compared to jatropha biodiesel blends, fig. 5(b), because jatropha SVO has relatively higher density and viscosity compared to jatropha biodiesel, tab. 1. Higher density and viscosity of jatropha SVO leads to larger size droplet formation, with droplets having higher inertia. As the chamber pressure increases from 1 to 9 bar, fuel droplets start concentrating near the centre of the spray because of increasingly denser chamber air, which offers stiffer resistance to the fuel droplets and forces them to spread in radial direction, thus increasing the cone angle and the spray area. The spray areas of J100, J20, and J5 are found to be 38.23, 36.29, and 31.95 cm^2, respectively, fig. 5(a), which is higher than JB100, JB20, and JB5 (35.41, 33.82, and 30.52 cm^2, respectively), fig. 5(b), at 9 bar chamber pressure.

Since all the blends of jatropha oil and jatropha biodiesel are more viscous than diesel and also have higher densities, the droplets formed inside the constant volume combustion chamber after being injected by the injector (at 200 bar pressure) will be relatively larger. These droplets will be heavier and will experience higher van-der-Waals forces amongst themselves therefore will be affected by the ambient pressure to a relatively lower degree compared to mineral diesel, which gives rise to relatively smaller droplet size distribution. Since the injectors normally have a tapered nozzle, the ambient pressure will not be able to significantly affect the direction of droplets relative to diesel droplets therefore their penetration, cone angle and spray surface area will be higher than diesel, as observed in fig. 2, 3, and 5.

Spray images analysis

The light is generated by a white light source and it gets scattered after interaction with the fuel droplets. This results in a gradual change in the light intensity level along the spray length which is captured by the camera. Higher intensity level indicates higher fuel droplet density. Intensity for different pixels in images is calculated by RGB values using the following formulae:

$$I = \frac{R + G + B}{3} \tag{1}$$

The range of intensity level is from 0 to 255 for this study. Value of intensity varies from 0 to 255; here 0 for absolute black colour and 255 for absolute white colour.

High density droplets in the spray have higher brightness level compared to those with low density. The droplets of low density in the spray indicate that the number of droplets has decreased either by active atomization or evaporation of fuel droplets in the outer and end regions. Thus the reflected light intensity level shows the density level of fuel droplets in the spray Kim *et al*. [17]. Figure 6 represents the schematic of typical fuel spray and indicates measurement locations chosen for the present investigation.

Two measurement locations fig. 6 were selected in the axial direction of the spray, 6.77 cm and 10.59 cm from the nozzle based on the calculations, which suggest that spray breakup takes place at 6.4 cm from the nozzle and the fuel spray gets completely atomized 10 cm downstream in the axial direction from the nozzle. The equations used for calculation were given by Lee and Park [18], using "KH–RT breakup model".

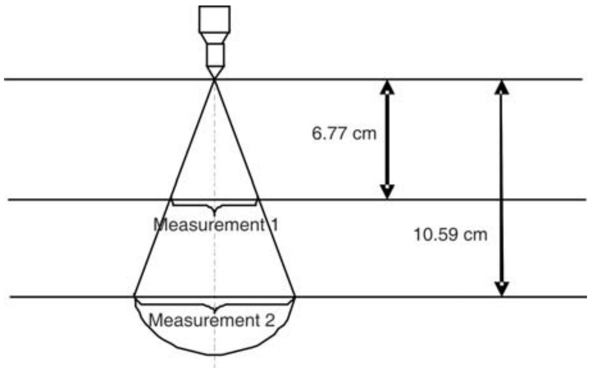

Figure 6. Spray pattern and measurement locations

Atomization of jatropha blends at various chamber pressures

Pixel intensity level of jatropha blends vis-à-vis mineral diesel at 6.77 cm from the nozzle at various chamber pressures is shown in fig. 7.

Pixel intensity level of jatropha blends vis-à-vis mineral diesel at 10.59 cm from the nozzle at various chamber pressures is shown in fig. 8.

It can be clearly observed from figs. 7 and 8 that all jatropha blends (except J100) are in almost completely atomized form at measurement location 2. At measurement location 1, the pixel intensity level saturates, suggesting extremely dense zone for fuel droplets (droplet cloud) for all jatropha blends as well as mineral diesel.

Mineral diesel droplets are smaller compared to the biodiesel and SVO blends. It is possible that diesel droplets penetrate all the way without dispersing. The vaporisation characteristics of the test fuels are very different from each other and there is a complex coupling between the spray droplet size, injection pressure, ambient pressure and fuel vaporisation characteristics. At relatively higher ambient pressure (9 bar), it is possible that the small droplets of diesel face higher resistance because of increased air density and atomize earlier. This could be the reason for higher light intensity obtained at higher ambient pressure.

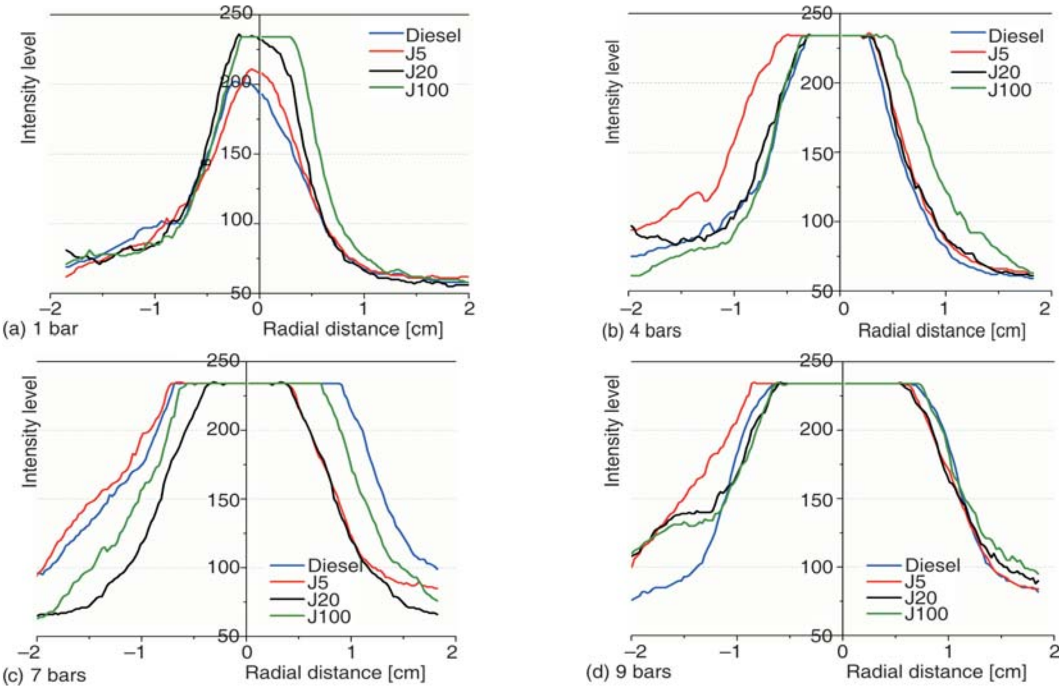

Figure 7. Pixels intensity level of jatropha blends at 6.77 cm from nozzle at various chamber pressures

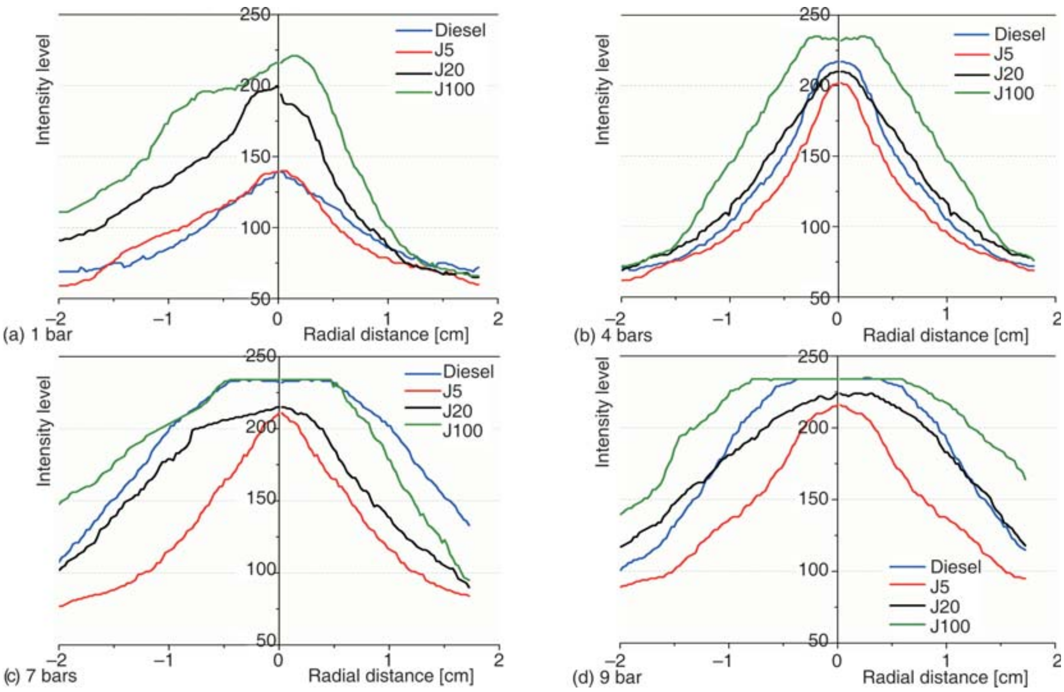

Figure 8. Pixels intensity level of jatropha blends at 10.59 cm from nozzle at various chamber pressures

Effect of increasing chamber pressure on atomization of jatropha blends

20% jatropha blend (J20) is chosen to understand the effect of increasing chamber pressure on the atomization of the test fuel. Figure 9 shows the pixel intensity of J20 at two different measurement locations (1 and 2) under varying chamber pressures.

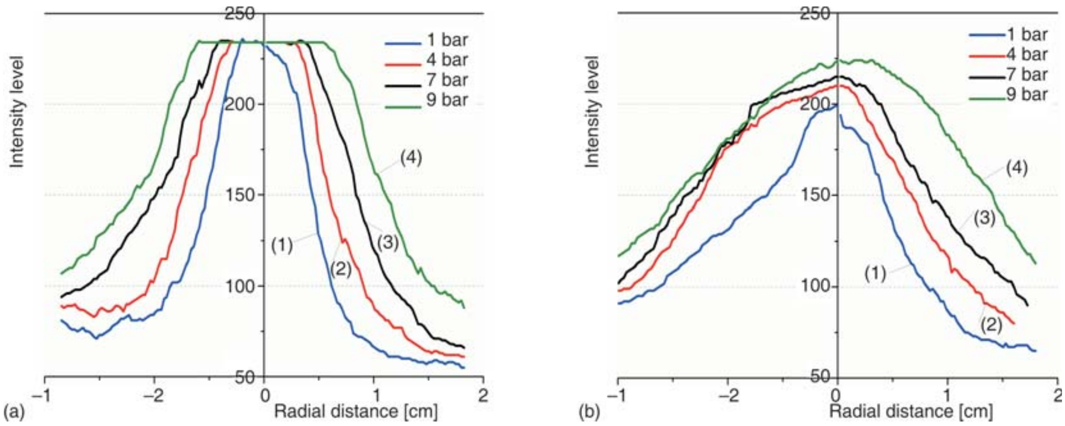

Figure 9. Effect of increasing chamber pressures on pixel intensity of J20 (a) at 6.77 cm and (b) at 10.59 cm from the nozzle

The total length of peak intensity level of J20 fuel gradually increases with increasing chamber pressure at measurement location 1, fig. 9(a). As one moves radially outwards, the intensity level decreases rapidly, indicating decreasing number of fuel droplets in this direction. This also indicates that at measurement location 1, J20 droplets have relatively poor atomization state, fig. 9(a), and most of the droplets are clustered together (droplet cloud). At measurement location 2 on the spray axis, J20 droplets are in a relatively improved atomization state and therefore spread more uniformly, fig. 9(b). Table 2 gives summary of length of peak intensity levels observed for different jatropha blends at different ambient pressure conditions.

Table 2. Length of peak intensity level of jatropha blends at two measurement locations

Fuel	Total length [mm] of peak intensity levels at 6.77 cm				Total length [mm] of peak intensity levels at 10.59 cm			
	1 bar	4 bar	7 bar	9 bar	1 bar	4 bar	7 bar	9 bar
Diesel	0	6	15.7	16.1	0	0	5	7
J5	0	9.5	13	16	0	0	0	0
J20	4	8	10.5	17.5	0	0	0	0
J100	7	11.5	17.5	19.5	2	7.5	10.5	14.5

It can be observed from this tables that the jatropha blend droplets (except J100) are in more uniform atomization state at measurement location 2 compared to measurement location 1.

Also the length of peak pixel intensity increases with increasing chamber pressure and increased jatropha oil concentration in the blend.

Atomization of jatropha biodiesel blends at various chamber pressures

Pixel intensity level of jatropha biodiesel blends vis-à-vis mineral diesel at 6.77 cm from the nozzle at various chamber pressures is shown in fig. 10.

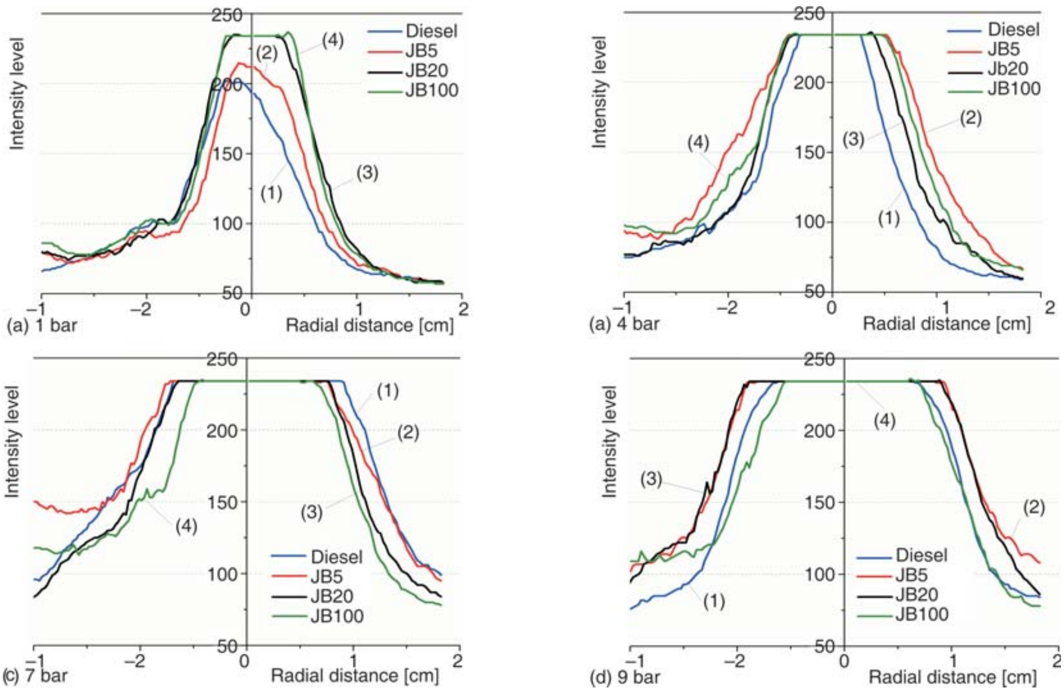

Figure 10. Pixels intensity level of jatropha biodiesel blends at 6.77 cm from nozzle at various chamber pressures

At 1 bar chamber pressure, fig. 10(a), the jatropha biodiesel and blends show similar results as jatropha SVO. JB100, shows highest pixel intensity level followed by JB20, JB5, and diesel. At chamber pressure of 4 bar, fig. 10(b), the length of peak intensity level of JB100 (9.5 mm) is higher as compared to JB20 (7.5 mm), JB5 (6.5 mm), and diesel (6 mm). At chamber pressure of 7 bar, mineral diesel shows highest droplet intensity level followed by JB100, JB20 and JB5. At 9 bar chamber pressure, fig. 10(d), diesel, JB5, and JB20, show similar peak droplet intensity levels, which are higher than JB100, tab. 3. Pixel intensity level of jatropha biodiesel blends vis-à-vis mineral diesel at 10.59 cm from the nozzle at various chamber pressures is shown in fig. 11.

At 1 bar chamber pressure, the droplets density level is higher at measurement location 2 compared to measurement location 1. JB100 had highest droplet density level followed by JB20, JB5 and diesel. JB20 and JB5 exhibit relatively superior atomization states compared to JB100 fig. 11(a). Figure 11 shows that jatropha biodiesel demonstrates lesser degree of atomization at measurement location 2 compared to measurement location 1. This is because biodiesel

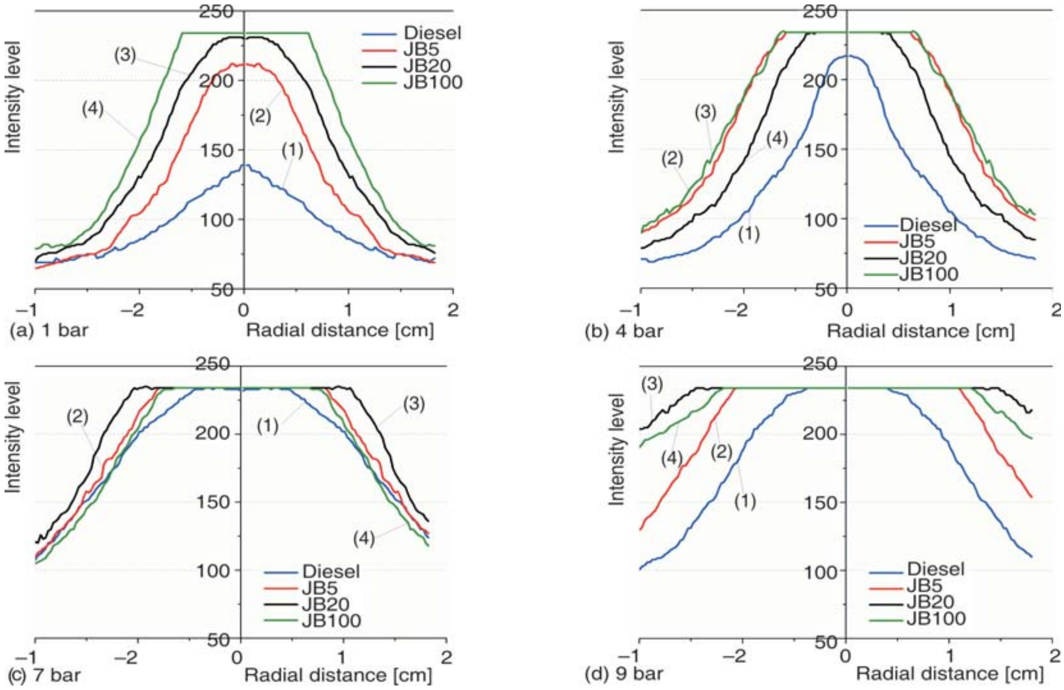

Figure 11. Pixels intensity level of jatropha biodiesel blends at 10.59 cm from nozzle at various chamber pressures

has higher density compared to mineral diesel and it also has relatively higher spray penetration length compared to mineral diesel, fig. 2. Degree of atomization of fuel around the spray centreline decreases with increasing chamber pressure due to increased resistance to spray droplets from denser chamber air. These observations show opposite trend to what is observed with jatropha oil blends.

Effect of chamber pressure on atomization of jatropha biodiesel blends

JB20 is selected to understand the effect of increasing chamber pressure on fuel atomization. Figure 12 shows the pixel intensity of JB20 at two different measurement locations (1 and 2) under varying chamber pressures.

The total length of peak intensity level of JB20 gradually increases with increasing chamber pressure at measurement location 1, fig. 12(a). As one moves radially outwards, pixel intensity level decreases rapidly, indicating decreasing number of biodiesel droplets in this direction. This also indicates that at measurement location 1, JB20 droplets have relatively poor atomization state, fig. 12(a), and most of the droplets are clustered together to form droplet cloud. At measurement location 2, JB20 droplets are in a relatively improved atomization state at 1 and 4 bar chamber pressures and are spread more uniformly, fig. 12(b). However at higher chamber pressures of 7 and 9 bar, intensity level of droplets saturates indicating presence of biodiesel droplets clustered together because of higher spray jet penetration, which is a different behaviour compared to jatropha oil blends. Table 3 summarises the length of peak intensity levels observed for different jatropha biodiesel blends at different ambient pressures.

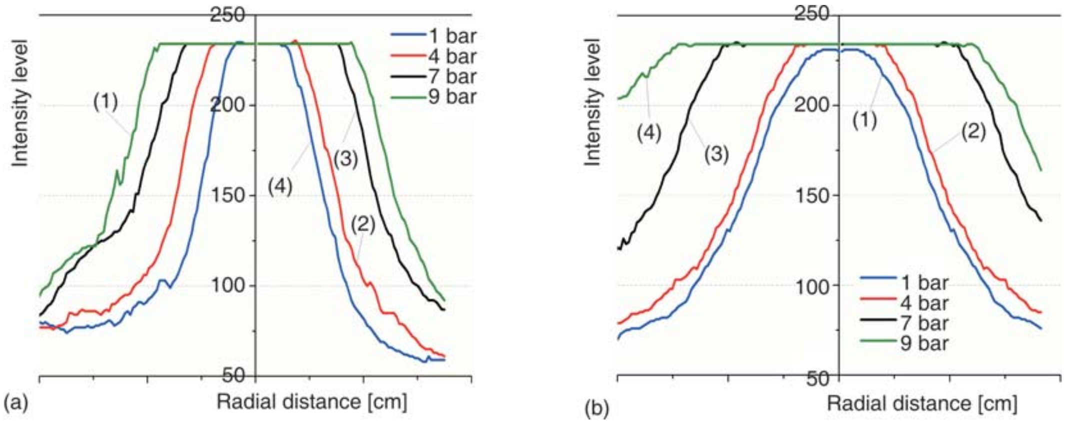

Figure 12. Effect of increasing chamber pressures on pixel intensity of JB20 (a) at 6.77 cm and (b) at 10.59 cm from the nozzle

Table 3. Total length of peak intensity level of jatropha biodiesel blends at two measurement locations

Fuel	Total length [mm] of peak intensity levels at 6.77 cm				Total length [mm] of peak intensity levels at 10.59 cm			
	1 bar	4 bar	7 bar	9 bar	1 bar	4 bar	7 bar	9 bar
Diesel	0	6	15.7	16.1	0	0	5	7
JB5	0	6.5	14	19	0	12	16.5	20.5
JB20	4.5	7.5	15.5	20	0	5.5	18.6	22.5
JB100	5.5	9.5	16	22.2	11.5	13.5	22.5	24.5

In summary, the fuel spray tends to spread radially faster for biodiesel blends at measurement location 2, whereas it remains mostly concentrated closer to the spray axis in case of straight vegetable oil blends. This is one possible reason why spray penetration lengths are higher for straight vegetable oil blends compared to biodiesel blends.

Discussion

It would be difficult to compare the results of the present study with previously reported results of spray characterization because the experimental conditions are quite different. A brief discussion has been explained for the results obtained by comparing it with a similar work. As anlysed by Roisman *et al*. [16] spray tip velocity shows similar trend as that of spray tip penetration results in the present study, fig. 2. It also shows that the spray tip penetration and spray tip velocity are directly related. They have shown that the spray tip velocity decreases with the increasing ambient pressure. Backofen *et al*. [19] also analyzed spray parameters at different chamber pressure and found similar trends for spray penetration and spray cone angle as reported in the present study.

Conclusions

SVO and biodiesel have different viscosity, density, and volatility characteristics compared to mineral diesel. In this research, these main properties were brought closer to diesel by blending SVO and biodiesel derived from jatropha oil with mineral diesel and investigating the spray characteristics using a constant volume spray chamber under varying chamber pressures followed by analysis of the spray images. The spray tip penetration of the test fuels decrease as the chamber pressure increases. Spray tip penetration of J100 was highest, followed by J20, J5 and diesel, respectively, among the SVO blends. Similarly, JB100 showed higher spray tip penetration followed by JB20, JB5, and diesel, respectively. The spray cone angle increased as the chamber pressure increases for all test fuels. Initially at 1 bar chamber pressure, cone angle is higher for biodiesel blends and diesel compared to SVO blends because of relatively superior atomization of these fuels. However at the higher chamber pressure (9 bar), it was observed that cone angle of SVO blends is higher compared to biodiesel blends. The cone angle of J100 was found to be highest for all chamber pressures condition followed J20, J5, and diesel, respectively. Similarly, cone angle of JB100 was highest for all chamber pressures conditions followed by JB20, JB5, and diesel, respectively. The spray area also increased with increasing chamber pressure. The spray area of J100 was highest for all chamber pressures followed by J20, J5, and diesel, respectively, and similar results were obtained for biodiesel blends.

In the analysis of pixel intensity level of the photographic images, it was concluded that peak intensity level length was higher at measurement location 2 in comparison to measurement location 1. As the chamber pressure increased from 1 to 9 bar, the pixel intensity values increased and the length of peak intensity level also increased. J20, J5, and JB20, JB5 showed superior spray and atomization characteristics compared to J100 and JB100, respectively, at all chamber pressure conditions. At higher chamber pressures, large number of biodiesel droplets cluster together because of higher spray penetration length, which is a significantly different spray behaviour compared to jatropha SVO blends.

References

[1] Schnorbus, T., *et al*., New Challenges for Combustion Control in Advanced Diesel Engines, *MTZ, 69* (2008), 4, pp. 18-26
[2] Kuthalingam, A. B., *et al*., Performance and Emission Characteristics of Double Biodiesel Blends with Diesel, *Thermal Science, 17* (2013), 1, pp. 255-262
[3] Delfort, B., *et al*., Glycerine for New Biodiesel Formulation, Oil and Gas Science and Technology, Rev IFP, 63 (2008), 4, pp. 395-404
[4] Gao, Y., *et al*., Experimental Study of the Spray Characteristics of Biodiesel Based on Inedible Oil, *Biotechnology Advances, 27* (2009), 5, pp. 616-624
[5] Ramadhas, A. S., *et al*., Performance and Emission Studies on Biodiesel-Liquefied Petroleum Gas Dual Fuel Engine with Exhaust Gas Recirculation, *Journal of Renewable and Sustainable Energy*, *2* (2010), 1, pp. 1-9
[6] Soid, S. N., Zainal, Z. A., Spray and Combustion Characterization for Internal Combustion Engines Using Optical Measuring Techniques, A review, *Energy, 36* (2011), 2, pp. 724-741
[7] Banhawy, Y. E., Whitelaw, J. H., Experimental Study of the Interaction between a Fuel Spray and Surrounding Combustion Air, *Combustion and Flame*, *42* (1981), pp. 253-275
[8] Kostas, J., *et al*., Time Resolved Measurements of the Initial Stages of Fuel Spray Penetration, *Fuel, 88* (2009), 11, pp. 2225-2237
[9] Klein-Douwel, R. J. H., *et al*., Macroscopic Diesel Fuel Spray Shadowgraphy Using High Speed Digital Imaging in a High Pressure Cell, *Fuel, 86* (2007), 12-13, pp. 1994-2007
[10] Fang, T., Lee, C. F., Bio-Diesel Effects on Combustion Processes in an HSDI Diesel Engine Using Advanced Injection Strategies, *P Combust Inst, 32* (2009), 2, pp. 2785-2792
[11] Agarwal, D., Agarwal, A. K., Performance and Emissions Characteristics of jatropha Oil (Preheated and Blends) in a Direct Injection Compression Ignition Engine, *Applied Thermal Engineering, 27* (2007), 13, pp. 2314-2323
[12] Pramanik, K., Properties and Use of jatropha Curcas Oil and Diesel Fuel Blends in Compression Ignition Engine, *Renewable Energy, 28* (2003), 2, pp. 239-248

[13] Kandpal, J. B., Madan, M., jatropha Curcas: A Renewable Source of Energy for Meeting Future Energy Needs, *Renewable Energy, 6* (1995), 2, pp. 159-160
[14] Park, S. H., *et al*., A Study on the Fuel Injection and Atomization Characteristics of Soybean Oil Methyl Ester (SME), *International Journal of Heat and Fluid Flow, 30* (2009), 1, pp. 108-116
[15] Seneschal, J., *et al*., Automatic System for Visualization and Characterization of High Pressure Diesel Sprays, *Proceedings ,* PSFVIP-4, 2003
[16] Roisman, I. V., *et al*., Effect of Ambient Pressure on Penetration of a Diesel Spray, *International Journal of Multiphase Flow, 33* (2007), 8, pp. 904-920
[17] Kim, H. J., *et al*., A Study on the Macroscopic Spray Behaviour and Atomization Characteristics of Biodiesel and Dimethyl Ether Sprays under Increased Ambient Pressure, *Fuel Processing Technology, 91* (2010), 3, pp. 354-363
[18] Lee, C. S., Park, S. W., An Experimental and Numerical Study on Fuel Atomization Characteristics of High-Pressure Diesel Injection Sprays, *Fuel, 81* (2002), 18, pp. 2417-2423
[19] Backofen, D., *et al*., Spray Characterization of Alternative Diesel Fuels, FISITA 2010, Budapast, 2010-A-054

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