A Comparison of Jatropha Methyl Ester and Diesel Non-evaporating Sprays

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Abstract

The present experimental study compares various spray characteristics of diesel and jatropha methyl ester (JME/ jatropha biodiesel) non-evaporating sprays. These sprays are studied in a specially fabricated high pressure chamber with optical access. The fuels were injected at injection pressures of 500, 1000 and 1500 bar into a nitrogen environment maintained at 20, 25 and 35 bar, respectively. First, the spray structure in terms of spray tip penetration and spray plume angle are compared. It is observed that the spray tip penetration is around 2 to 5% higher and the spray plume angle is around 7 to 17% smaller for JME as compared to diesel. This indicates a slower breakup for the jatropha biodiesel sprays. Droplet diameters are measured using the particle/droplet image analysis (PDIA) technique. For JME, around 5% higher droplet diameters are observed. Detailed probability distribution of droplets showed that jatropha biodiesel has more probability for larger droplet diameters (>18µm) and lesser probability for smaller droplet diameters (<18µm) which explains the overall SMD trend. The main reason for larger droplet diameters is the higher viscosity and surface tension of JME compared to diesel. The effect of fuel properties on the near nozzle structure is studied. A longer unbroken liquid length and narrower spray plume is observed for JME as compared to diesel indicating slower breakup.

Introduction

Recently, bio-fuels are being considered as important alternatives for petroleum-fuels because of their renewability. In particular, jatropha, pongamia and rapeseed methyl esters are being actively considered as petroleum-diesel alternatives [1, 2 and 3]. Many researchers have studied and reported various effects of using biodiesels on spray, combustion and emissions with respect to compression ignition (CI) engines ranging from very broad engine level tests to basic studies on liquid properties, spray structure and its implications [4 and 5]. When biodiesel are used in CI engines, both system response issues which are caused by response of engine systems to change in physical properties of fuel and effect of properties of fuel themselves are observed to influence the engine performance and emissions [6]. Examples of system response issues are higher injection pressure, changes in EGR percentage, etc. due to change of fuel. Examples of effect of fuel properties are shorter ignition delays and higher NO_x, etc. when biodiesel is used instead of diesel [6, 7 and 8.]. Due to higher viscosity of biodiesels, injection flow rate slightly reduces and droplet diameters are observed to increase [7]. Longer injection durations were required to compensate for lower calorific value of biodiesels [8]. Some researchers reported that reduction in radiation by biodiesel soot cause increase in NO_x [8]. Increase in EGR for reducing NO_x is observed to increase fuel consumption [9].

Studies on rapeseed methyl ester sprays show that biodiesel sprays have slightly lower injection velocities, higher spray tip penetration and narrower spray plume angles [10 and 11]. On the other hand, some researchers reported similar tip penetration for diesel and biodiesels [11 and 12]. Also, biodiesels have lesser tendency of inner nozzle cavitation compared to petroleum-diesel. In combusting sprays, lift-off length and liquid length were found to be more for biodiesel [13]. It is evident from the above discussion that use of biodiesels in engines requires detailed study of their physical and chemical properties and their influence on engine performance and emissions. As diesel engine combustion process is significantly influenced by spray characteristics, it is worthwhile to study the spray characteristics of biodiesels. Most of the spray studies on biodiesel have reported the comparison of spray structure of rapeseed and soybean-derived biodiesel and diesel. Very limited literature is available on detailed experimental study of jatropha methyl yester (JME). The main focus of the present study is to perform a comprehensive experimental study comparing the characteristics of diesel and JME sprays.

Experimental Setup and Methods

A schematic diagram of the experimental setup used in the present study is shown in Fig. 1. It consists of a high-pressure spray chamber which is designed withstand gas pressures up to 60 bar and is provided with quartz glass windows for spray visualization. The fuel supply line consists of a temperature-controlled fuel tank, a high-pressure fuel pump driven by an electrical motor, a common-rail and a solenoid operated common-rail diesel

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injector. The diesel injector is specially made with a single hole (190 µm) with its axis coinciding with the injector axis. Injector is vertically mounted on the top plate of the spray chamber. A standalone injector controller which is synchronized with timing of laser pulse is used to operate the injector. The common rail in conjunction with a high pressure fuel pump and a standalone closed-loop rail pressure controller maintains the injection pressure precisely within ±5 bar of the set pressure.

    The spray measurement system utilizes a diffuse light source consisting of a pulsed laser and a high efficiency diffuser to provide intense background illumination to the spray, a long distance micro scope to visualize the spray and a CCD camera (2048×2048 pixels resolution) to record the images. The laser pulse, injection timing and camera timing are synchronized enabling the timing of the injection event relative to the laser pulse. The spray is illuminated for a very short duration (~20 ns) by laser pulse to obtain time-frozen spray images.

Measurement of Spray Structure

    During the spray structure (spray tip penetration and plume angle) measurement, background illumination is provided by a high power halogen lamp. A high-speed camera with zoom lens is used to capture the spray images. The high speed camera is set to take around 65000 frames per second to capture the spray event with sufficient time resolution. The images are post-processed to obtain spray tip penetration and spray plume angle with time. Figure 2 shows an example of a post-processed spray structure image.

-------- Control signal   —·—·—Fuel line   ———— Nitrogen line
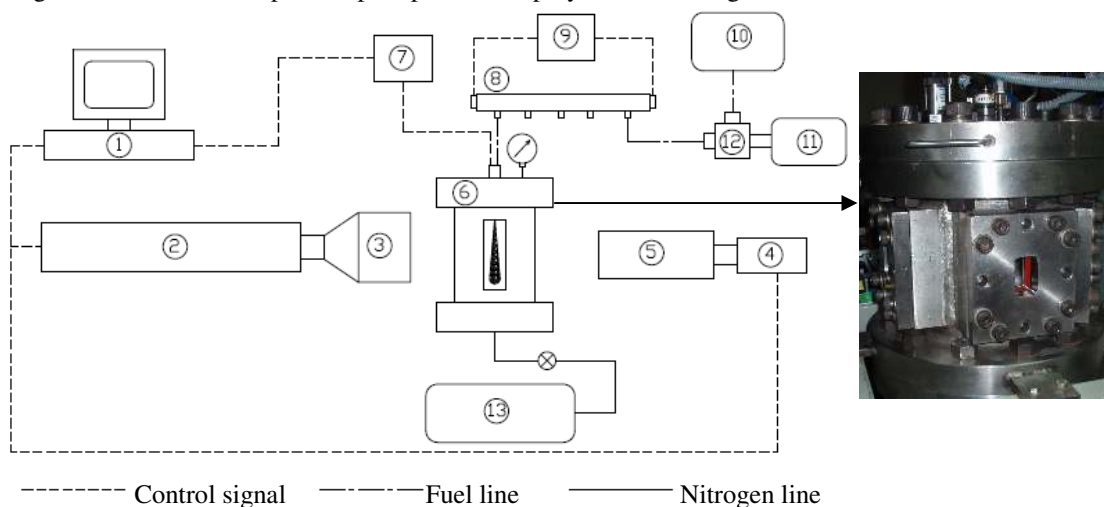
1)Computer, 2)Nd:YAG Laser, 3)High efficiency diffuser, 4)CCD Camera/High speed camera, 5)Zoom lens/Long distance microscope, 6)High pressure chamber, 7)Injector controller, 8)Higher pressure rail (9)Rail pressure controller, 10)Fuel tank, 11)Motor, 12)High pressure fuel pump, 13)N_2 cylinder
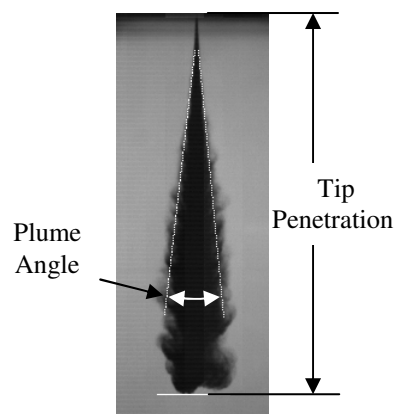
Fig. 1 Schematic of the experimental setup

Fig. 2 Illustration of processed spray structure image

Droplet Size Measurement

    A particle/droplet image analysis (PDIA) technique is utilized to measure the droplet sizes. PDIA is a technique being utilized extensively in the recent past to measure droplet sizes [14-18]. Recently, PDIA has been compared and validated with phase doppler anemometry (PDA) by Kashdan et al. [19]. This technique has advantages of visual record of droplets measured, particle shape information and lower cost over conventional

methods. A pulsed Nd:YAG laser along with a high efficiency fluorescence based diffuser are used for providing a very high intensity background illumination.   A long distance micro scope is used to zoom into a small area of around 2.5mm×2.5mm of the spray. Also, the long distance micro-scope has a narrow depth of focus which avoids defocused out of plane droplets. A laser pulse of around 7-ns is used to obtain time-frozen images of droplets. Droplet measurements were not possible during the early and mid-phase of the injection process as the spray is extremely dense. Thus, the measurements are performed at 1ms after the end of injection when the spray is relatively more dispersed. Measurements are taken at various geometric locations with respect to injector tip to encompass the entire spray. Approximate locations of measurements are shown in Fig. 3. Figure 3 also shows an example raw image obtained during measurement and a processed image which shows various droplets identified. Images from around 100 spray events are collected to sample considerably large number of droplets for a better statistical representation of the spray.
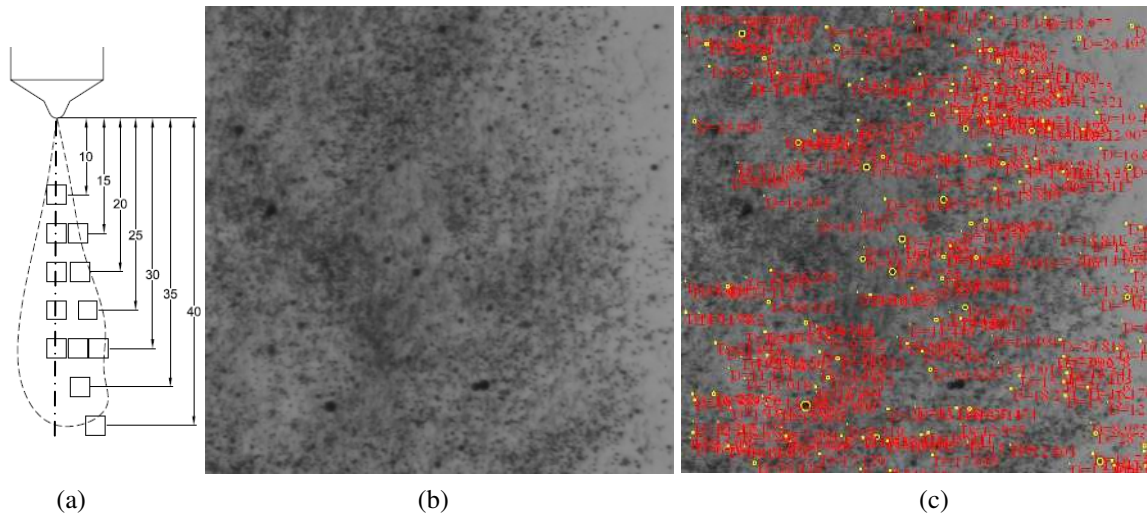

(a)   (b)   (c)

Fig. 3 (a) Approximate measurement locations (distance in mm), (b) Raw image (c) Processed image

Experimental Conditions

In the present study, three experimental conditions are considered which resemble the in-cylinder conditions of a typical compression ignition engine. Table 1 shows ambient gas pressure and injection pressure corresponding to these experimental conditions considered. The last column of the table shows the relevance of the experimental condition chosen to the engine operating point. Approximate in-cylinder density of gas is maintained in the spray chamber at cold temperature. All the tests are performed at a chamber temperature of 25°C. The fuel temperature is also maintained low to avoid evaporation of fuel. Table 2 compares the physical properties relevant to the present study for diesel and jatropha biodiesel. The density of biodiesel is around 7% higher, kinematic viscosity is about 70% higher and surface tension is about 15% higher for biodiesel.

Experimental Condition	Gas pressure (bar)	Injection pressure (bar)	Engine operating condition
P_{gas}=20, P_{inj}=500	20	500	Low speed, Low load
P_{gas}=25, P_{inj}=1000	25	1000	Medium speed, Medium load
P_{gas}=35, P_{inj}=1500	35	1500	High speed, High load

Table 1 Experimental conditions

Property	Diesel	JME
Density (kg/m^3)	814.8	869.3
Kinematic Viscosity @ 40°C (cSt)	2.5	4.22
Surface tension (mN/m)	26.7	30.7

Table 2 Comparison of physical properties

Results and Discussion
    In this section a comparison is made between various spray characteristics of diesel and jatropha biodiesel. First, results of spray structure are discussed followed by droplet measurement results and near-nozzle structure.

Spray Structure
    With respect to diesel engines two parameters namely spray tip penetration and spray plume angle are considered to be very important. While the former parameter describes the speed of travel of the spray the latter describes the lateral spread of the spray. These two parameters also provide qualitative information on spray breakup, entrainment of air and air-fuel mixing.
    Figure 4 shows a comparison of the spray tip penetration at various experimental conditions with time. The data shown are ensemble-averaged from 10 spray events. From the figure, it can be seen that the spray tip penetration rate is higher during the initial spray development and then it reduces. The change in slop of the penetration curve can be clearly seen in the figure. The point at which there is a change of slope also indicates enhancement of spray breakup and fuel-air interaction. Comparing spray at various injection pressures, this change in slop occurs early as injection pressure is increased which confirms that improved break-up and air entrainment is possible at higher injection pressures.
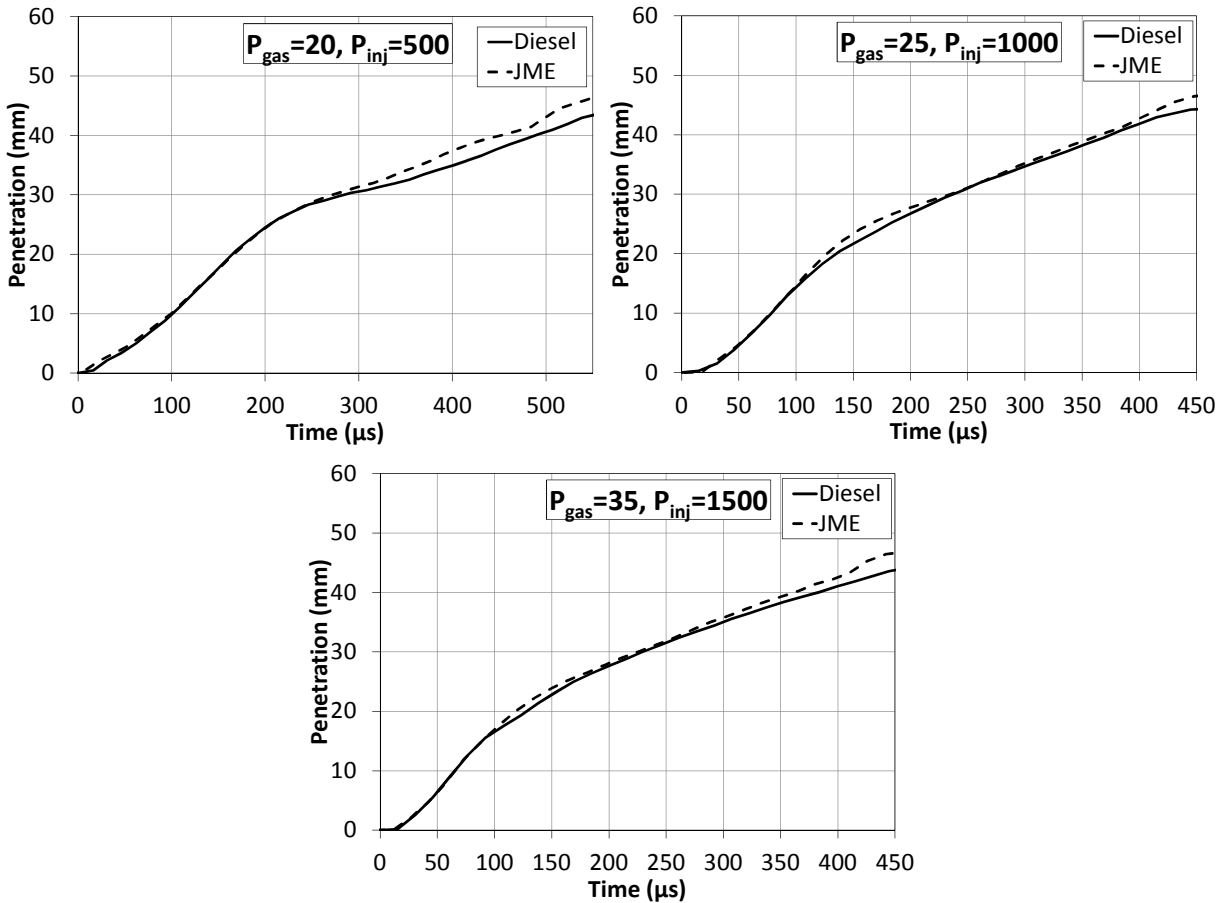
Fig. 4 Comparison of spray tip penetration at various experimental conditions

    A comparison of the spray tip penetration data for diesel and jatropha biodiesel shows that, in the initial stages of spray development where the breakup is not significantly achieved, the penetration is identical. Just after the change in slope, the penetration of biodiesel is seen to be slightly higher for biodiesel as compared to that of diesel. Quantitatively, the penetration of biodiesel is about 2 to 6% higher than that of diesel. Also, the difference reduces as injection pressure and chamber pressure are increased.
    Figure 5 shows a comparison of the spray plume angle between diesel and jatropha biodiesel. The spray plume angle of jatropha biodiesel is consistently smaller as compared to that of diesel by about 7% to 17%. A smaller spray plume angle indicates slower breakup and lesser air entrainment. Overall, the spray structure com-

parison shows that the spray breakup may slightly be slower for biodiesel which leads to a slightly higher penetration and smaller spray plume angle.
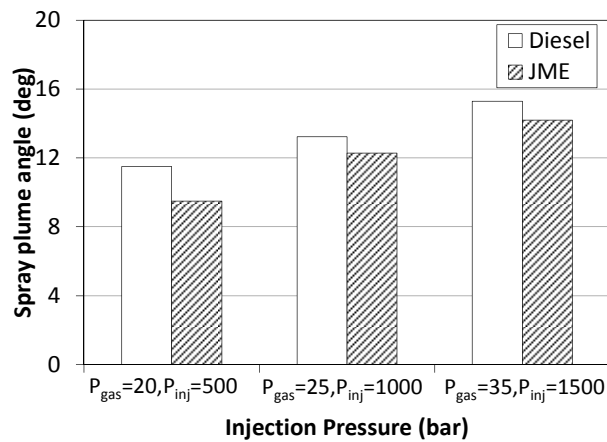

Fig. 5 Comparison of spray plume angle at various experimental conditions

Droplet size and distribution

From the spray structure study, jatropha biodiesel is expected to have slightly higher droplet diameters as compared to that of diesels spray. As mentioned earlier, measurement of droplet diameters is performed at around 1ms after the end of injection. Figure 6 shows the comparison of sauter mean diameter (SMD) for diesel and jatropha biodiesel. It can be observed from the figure that SMD decreases as injection pressure increases which indicates enhanced spray break-up. At the $P_{gas}=20$, $P_{inj}=500$ condition, the SMD is almost same for diesel and biodiesel. At the other two experimental conditions, jatropha biodiesel shows around 5% higher SMD as compared to diesel.
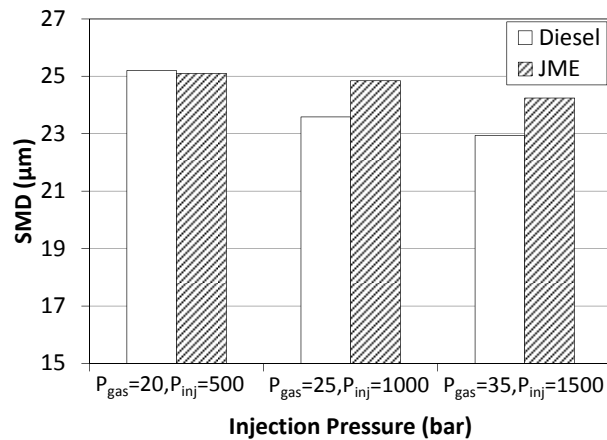

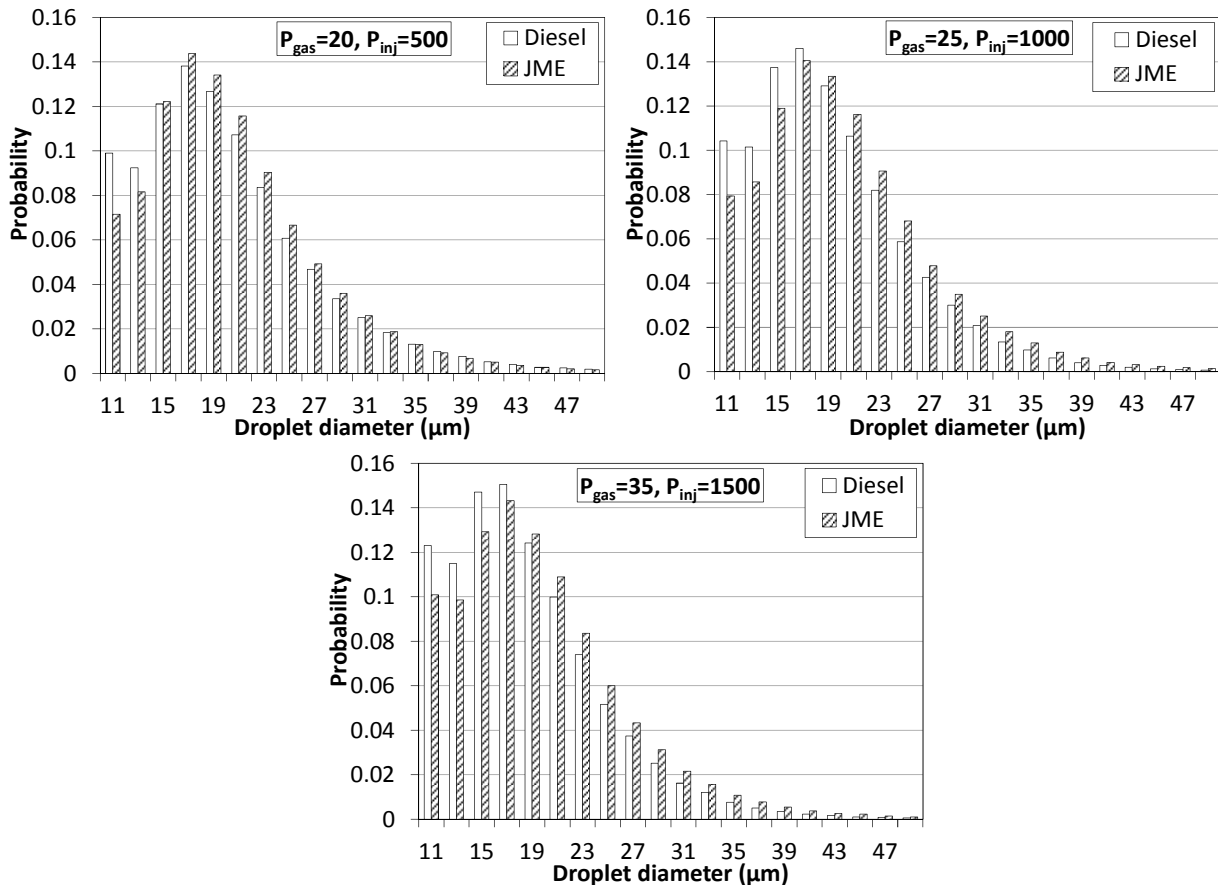Fig. 6 Comparison of droplet sizes at 1ms after end of injection

Fig. 7 Comparison of droplet size distribution at various experimental conditions

Figure 7 shows detailed probability distributions of droplet diameters at various experimental conditions. The figure clearly shows that diesel spray is associated with higher probability for small droplets as compared to JME. At P_{gas}=20, P_{inj}=500, even though diesel has large number of small droplets (<14µm), JME shows a larger percentage of droplets beyond 17µm. At P_{gas}=25, P_{inj}=1000 and P_{gas}=35, P_{inj}=1500 conditions, diesel shows a significantly higher number of smaller droplets which are < 18µm and biodiesel has a larger number of droplets of size > 18µm. Thus, the overall SMD is higher for jatropha biodiesel at these conditions. As one can expect evaporation of smaller droplets to be much faster, air-fuel mixing may be faster for diesel as compared to that of JME. One of the main reasons for increase in SMD of JME is the higher viscosity and surface tension of JME as compared to diesel fuel. Larger droplets do not lose their momentum as rapidly as the smaller droplets making them penetrate further. This explains the narrower spray exhibited by JME and a slightly higher tip-penetration as compared to diesel.

Near nozzle structure

The near-nozzle structure is studied with the same experimental setup which is used for the droplet measurement. As the liquid jet comes out from nozzle, instabilities grow in the boundary layer of liquid jet and finally cause breakup of liquid jet [20]. By imaging the near nozzle region and the length of the unbroken liquid core, qualitative inferences concerning the liquid breakup process and further spray development can be drawn.

Figure 8 shows images of the near nozzle structure for diesel and JME. At P_{gas}=20, P_{inj}=500, it can be clearly seen that the unbroken liquid length is around 25% higher as compared to that of diesel. Also, after the breakup process has started, the spread of the biodiesel spray is comparatively less. At P_{gas}=25, P_{inj}=1000, the unbroken liquid core is visible for JME whereas for diesel the breakup has started almost immediately at the exit of nozzle. At P_{gas}=35, P_{inj}=1500, the breakup has started immediately at the exit for both diesel and biodiesel. However, the spread of the spray is less for biodiesel. A longer unbroken liquid core indicates a slower growth of instabilities and delayed breakup for biodiesel. Also, a narrow spray indicates larger droplet diameters which tend to penetrate more in the axial direction.
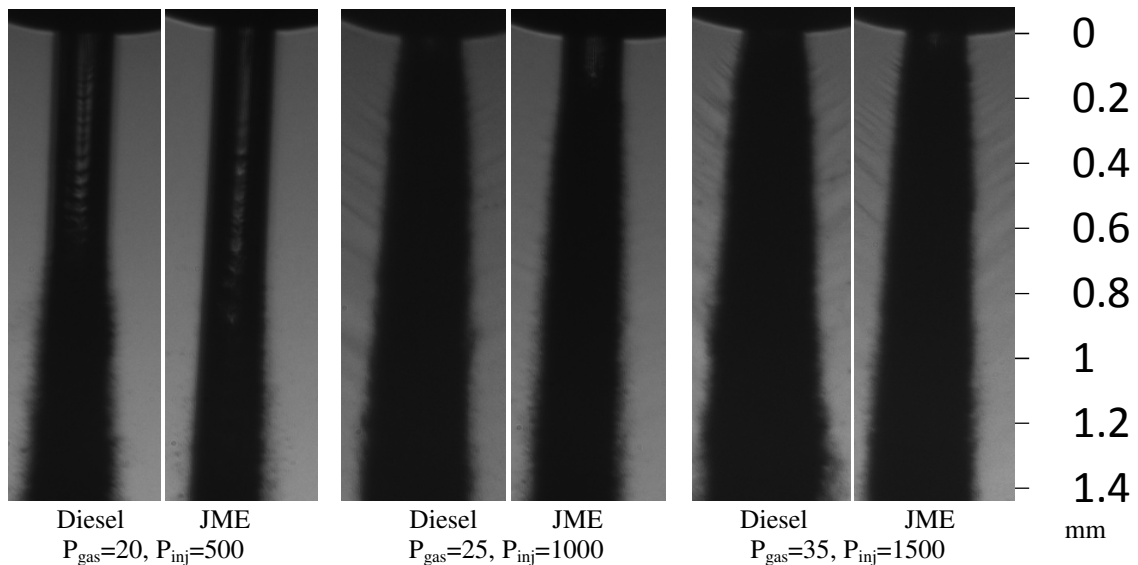
| Diesel | JME | Diesel | JME | Diesel | JME | mm |
| P_{gas}=20, P_{inj}=500 | | P_{gas}=25, P_{inj}=1000 | | P_{gas}=35, P_{inj}=1500 | | |

Fig. 8 Comparison of near-nozzle structure at various experimental conditions in the middle of injection duration

Summary

The following main inferences can be drawn from the above comprehensive experimental study on diesel and jatropha biodiesel spray characteristics

- In the initial stages of spray development, when the breakup is not significantly progressed, the spray tip penetration is same for diesel and jatropha biodiesel. Jatropha biodiesel penetrates faster at later stages of the spray evolution.
- The spray tip penetration is higher for jatropha biodiesel by about 2 to 6% as compared to that of diesel. Also, the difference in spray tip penetration reduces as the injection pressure increases.
- The spray plume angle is observed to be narrower for biodiesel by about 7 to 17% as compared to diesel. A narrow spray plume angle indicates delayed breakup process and larger droplet diameters for biodiesel.
- The droplet size measurement at 1-ms after end of injection using the PDIA technique revealed that SMD for the jatropha biodiesel is around 5% higher as compared to diesel.
- The droplet probability density distribution showed that probability of smaller droplets (<18μm) is more in the diesel spray as compared to the jatropha biodiesel spray. This explains the higher SMD for the jatropha biodiesel spray.
- A longer unbroken liquid length and narrow spread of spray is observed for jatropha biodiesel in the near nozzle region which indicates delayed breakup process for biodiesel sprays.
- The higher viscosity (about 70% higher than diesel) and surface tension (about 15% higher than diesel) of jatropha biodiesel are attributed for the slower breakup and larger droplet diameters.

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