Experimental Investigation and Spray Characterization of Liquid Jet Atomization of Conventional Fuels and Liquid Bio-Fuels

Soumik Mahapatra[1*], Souvick Chatterjee[1], Swagata Shannigrahi[2], Achintya Mukhopadhyay[1], Swarnendu Sen[1]
[1]Mechanical Engineering Department, Jadavpur University, India
[2]Automobile Engineering Department, MCKV Institute of Engineering, India
hisoumik@gmail.com, souvickchat@gmail.com, swagatashannigrahi@gmail.com,
a_mukho@rediffmail.com and sen.swarnendu@gmail.com

Abstract

Liquid atomization has always been a key topic of research in both academic and industrial world because of its importance from both fundamental and applied perspective. The application of efficient atomization ranges from biomedical purposes, inkjet printers and others in the micro scale to Gas Turbine and I.C. Engines in the macro world. Efficient atomization facilitating combustion is crucial for the macro-scale application and is addressed in this study. In this work, using different experimental techniques, fuel spray characteristics like spray cone angle, breakup length, droplet size and velocity distributions are studied. Simple shadowgraphy technique has been used to measure the spray cone angle. The breakup length are measured using an innovative image processing algorithm on images obtained using a laser based imaging technique. In addition, Phase Doppler Particle Analyzer (PDPA) is used to measure the droplet size and velocity. The commercially available fuel injection system used here allowed us to vary the injection pressure over a wide range. Also observed, is the effect of change in viscosity of the fuel on the breakup length and the spray cone angle. Tests were carried out for different commercially available fuels like diesel, kerosene and also bio-fuels like vegetable oils.

Introduction

Transformation of liquid jet into droplets is a study of utmost importance owing to the rich scope of its application. Such applications cover variety of industries ranging from heat treatment of electronic equipment to petroleum refining and chemical combustion and from gas turbine/diesel engines to nuclear reactors, medicine, printing and agriculture in the form of crop spraying. In the process of atomization, a liquid jet or sheet is disintegrated by the kinetic energy of the liquid itself, or by exposure to high velocity air or gas [1]. The quality of atomization is determined to a large extent by the design of the atomizer and properties of the fluid. To study the efficiency of this atomization process, it is important to monitor the important parameters involved in this phenomenon - spray cone angle, breakup length, droplet size and velocity. In particular, fuel flexibility of commercially available injectors and their adaptability to bio-fuels needs to be assessed. Easy and accurate measurement techniques for measurement of these parameters are yet to established and hence addressed herewith. A commercial nozzle is used for our study which is attached to a fuel injection system that allowed us to vary the injection pressure from 10 bar to 150 bar.

There have been plenty of reported literatures describing methods to measure spray cone angle for nozzles of different kind. Spray cone angles of traditional diesel injectors were studied by Varde [2] and Dan et. al [3]. Both these studies reported variation of spray cone angle with ambient and injection pressure. Since, we kept the ambient pressure to be atmospheric and varied the injection pressure over a broad range these two works are mention worthy. Varde [2] reported that cone angle increased as ambient pressure increased from 1 MPa to 3.3 MPa, while with an injection pressure rise from 50 to 125 MPa, cone angle could increase, decrease or remain the same depending on the injector exit orifice length to diameter ratio. Dan et. al [3] limited their injection pressure to 18 MPa and showed similar variation of spray cone angle with ambient pressure variation from 0.2 to 4.8 MPa. Apart from these standard diesel injectors, there have been plenty of studies for measurement of spray cone angles for effervescent atomization [4; 5], splash plate nozzles [6; 7], flashing jet sprays [8], airblast atomizers in the presence of strong swirl flowfield [9; 10] or simple pressure swirl atomizers [11].

There exist mainly two different techniques for determining the cone angle [12]- digital imaging and patternation. A high speed camera and an optical patternator are some high end devices in this context. While the former uses a camera with a high frame rate, in the latter a light sheet generated by a diode laser and collimating lens is used to probe the spray throughout a plane perpendicular to its centerline [13]. We used a digital SLR

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* Corresponding author: hisoumik@gmail.com

camera along with a halogen light source to obtain shadowgraph images from which the cone angle is calculated using a Java based image processing software called ImageJ. (v1.45) developed at National Institutes of Health (NIH). Also used is a simple mechanical radial patternator to measure the radial variation of volume flux of the fuel, which using simple trigonometry provides the spray cone angle and the two methods are found to give similar results.

The length of the continuous core of liquid jet is known as the breakup length. Both the underlying physics of the problem and determination of this length with varying parameters like fluid and injection pressure are crucial for the study of atomization. Studies indicate an increase of breakup length followed by a decrease with increasing Weber number, which is a ratio of inertia to surface tension [14; 15]. Also, the same is known to increase with an increase in the jet velocity as reported by Huang et. al [16; 17]. Variation of the breakup length with increase in injection pressure for different fluids has been reported by Lin et. al [18].

A number of techniques have been used over the years for measurement of this breakup length. Photography, mostly shadowgraphy, is the most commonly used method [19-21] but shadowgraphy often gives erroneous results. Another technique, known as the electrical conductivity technique, is based on the conduction of electricity along the length of the continuous liquid jet downstream of the nozzle [22]. An interesting work noteworthy in this context is by Laryea et. al [23] wherein investigation of breakup length of a charge induced electrostatic pressure swirl nozzle has been conducted. A novel technique, based on optical connectivity of liquid jet, has been proposed Charalampous et. al [24], where the jet is illuminated from within the nozzle by a laser beam. Other techniques used for measurement of breakup length include X-Ray absorption [25; 26] and ballistic imaging [27; 28] which require advanced equipments, not commonly available. In this paper, we describe a novel photography technique for measurement of the breakup length that does not require the use of any high speed camera or presence of electricity. The breakup length is obtained by simple processing the obtained images using MATLAB. Hence, the described method can prove to be very feasible, quick and accurate for determining break up length.

Spray characteristics study remains incomplete without the study of droplet and velocity distribution. Use of modern day reliable and versatile technique like Phase Doppler Particle Analyzer (PDPA) [29] providing real time velocities and drop-size distribution has proved fruitful. Droplet size distribution using this apparatus has been in use for quite some time now. Different types of liquid jets, namely planar [30], cylindrical [31] and annular [32; 33] were investigated using PDPA for measurement of these two important spray characteristics. Other notable spray works using PDPA include that of agricultural sprays, intermittent spray using common rail system [34], monodisperse droplets [35], spray in petrochemical industry [36] etc. In this work, we varied the injection pressure and obtained the droplet and velocity distribution for diesel.

Experimental Methods

The basic experimental apparatus consisted of a high pressure fuel injection system which is comprised by Nozzle tester apparatus (Model H-S/KDEP 99A), high pressure pipes and a commercially available injector. Three different fluids were studied namely diesel, kerosene and a biodiesel derived from edible sunflower oil. Spray cone angle, spray break-up length were measured for the nozzle with variation in injection pressure for each fuel. However, droplet size and velocity were measured for diesel only.

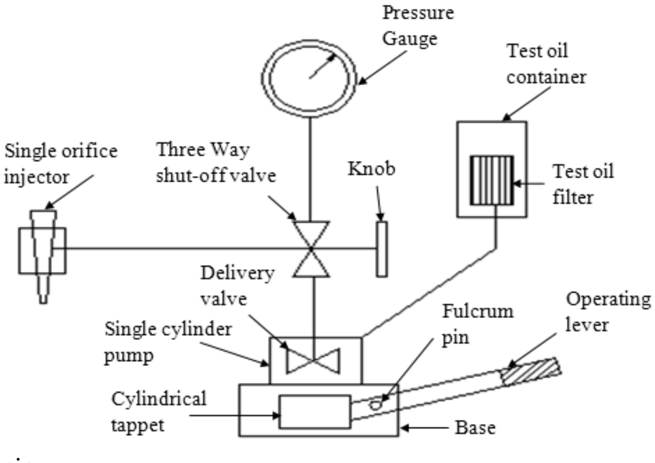

Figure 1 Basic layout of the nozzle tester and injector.

Figure 1 shows the schematic diagram of the basic experimental apparatus. It consists of (a) Injection Pump mounted on a base and operated manually by hand lever (b) Test oil container with filter and (c) Three way valve, pressure gauge and high pressure pipes for connecting the injector.

Liquid properties of the different test fuels at 25°C temperature are given below in table 1.

Table 1 - Properties of different fuels at 25°C

Test fuel	Kinematic viscosity (centistokes)	Density (gm/cc)
Kerosene	2.71	0.81
Diesel	4.2	0.80
Sunflower biodiesel	6.1	0.86

Spray Cone Angle

The spray cone angle is an important spray characteristic which describes spread of the spray in its applications. In the literature, different techniques for measurement of this are found but they lack a consensus. We measured the angle by direct visualization of the images using the definition of the same as the angle formed by two straight lines drawn from the injector tip to the outer periphery of the spray at a specified distance downstream from the nozzle. Higher spray cone angles ensure wider distribution of spray. A secondary method using a mechanical patternator was also used to monitor the radial volumetric distribution of the spray which also leads to a quantitative value of the spray angle.

i. Shadowgraph

Light shadowgraphy is the most commonly employed experimental means for evaluating the spread of the spray. A schematic of the arrangement is shown in Figure 2 below. In this method, a 1000W linear halogen lamp was used to illuminate the spray. The camera was positioned in front of the spray. Videos of the spray were recorded using a 12 Megapixel digital single reflex camera (DSLR) camera (Model Pentax kx) with an 18-55 lens at a standard definition of 640 x 416 pixels at 24 frames per second. Care was taken to ensure that all the images, extracted from the recorded videos, had exactly same brightness, contrast and dimensions (pixel wise), to minimize discrepancy in results. These images were further processed using image processing software called ImageJ® to calculate the spray cone angle. A minimum of five images at a particular pressure were considered for evaluating the spray cone angle. All measurements were made at 10 mm downstream the nozzle flow (as shown in Figure 3).

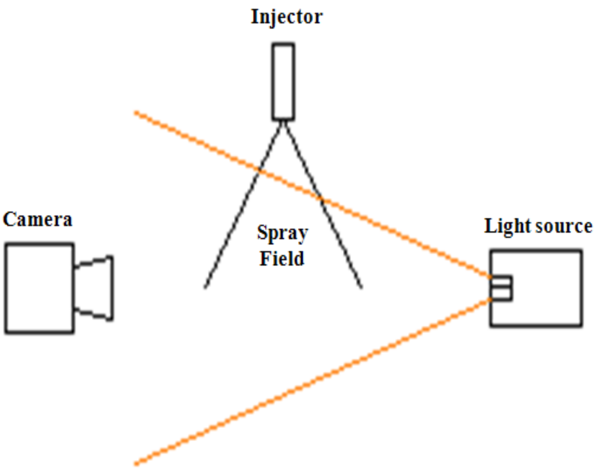

Figure 2 Optical arrangement to measure spray cone angle.

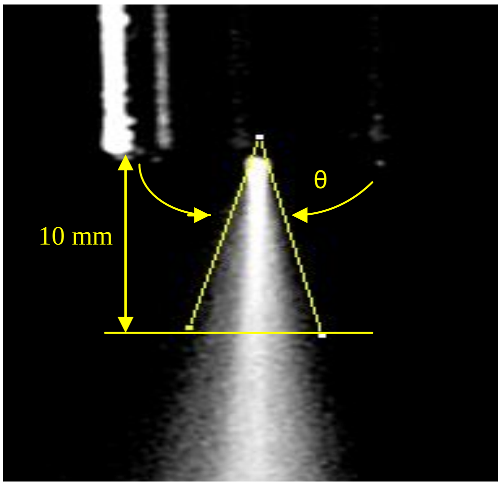

Figure 3 Definition of Spray Cone Angle.

Mechanical Radial Patternator

The term used to define distribution of spray is Patternation and the device which measures this distribution is called Patternator. For our purpose, a mechanical patternator was constructed from glass cubicles (Figure 4), each of 50 mm height and 10 x 10 mm^2 cross section. The wall of the cubicles was found to be approximately 1 mm thick. A total of 100 such cubicles were taken and attached on a perplex glass plate of dimensions 305 mm x 305 mm x 8 mm thickness. The patternator was placed at a distance of 75 mm from the centerline of the nozzle and its alignment was tested using a plumb line. Five shots of spray were considered before taking readings since a higher number caused spillage over from the central cubicle onto others or outside, while a lower number caused difficulties in measurement. A syringe of capacity 2 ml was used to collect the volume of gathered fluid from the cubicles. Graduations on the syringe body indicated a least count of 0.1 ml. The lower meniscus was chosen as the value to be noted in all cases.

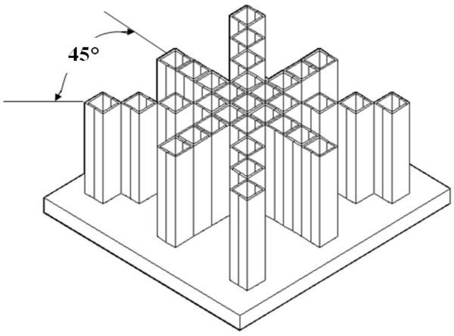

Figure 4 Mechanical patternator.

Breakup Length

Breakup length measurement has always been a challenging task in spray characteristic study. Real time visualization has been facilitated by the availability of high speed camera. But interpretation of breakup length from these images is still a challenging task. In this work, we propose an innovative technique for this measurement. The method proved fruitful for images obtained using a simple DSLR camera and hence, an expensive high speed camera is avoided in this study.

The basic principle of spray visualization in this regard is Mie-scattering. Mie-scattering refers to scattering of light by particles of size comparable to the wavelength of incident light. In such processes, there is no permanent exchange of energy between light and matter. Light used for illuminating the spray structure consisted of a 1 mm thick vertical sheet of Nd:YAG pulsed laser of wavelength 532 nm. The illuminated sheet passed through the centerline of the injector. The frequency of pulsations was kept at maximum value (158 Hz). The DSLR camera was positioned perpendicular to the laser light plane and operated in video mode. At a particular pressure, many images were extracted from the video recorded which were processed in MATLAB for calculation of breakup length. The algorithm used for the same is explained in the following section. A schematic of the arrangement is shown in Figure 5 below.

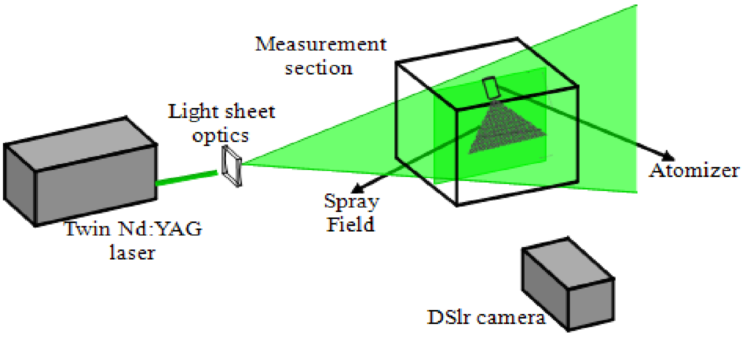

Figure 5 Optical arrangement to measure spray break up length.

Image Analysis

We define breakup length as the distance from where the liquid jet tends to shed particles from the side thus resulting into a dispersed structure. The method, used in this work, to process the images in MATLAB, is best illustrated in the Figure 6. For every axial distance y_i (pixel row), the peak green intensity value (I_{peak}) and position of the same (X_{peak}) is obtained. Then, for a particular y_i, traversing on either side of the X_{peak}, the positions are obtained (X_{max} and X_{min}) after which the green intensities drop below a specified thresold value I_{crit}. This leads to the definition of Δx for each y_i as

$$\vartriangle x = X_{max} - X_{min}$$

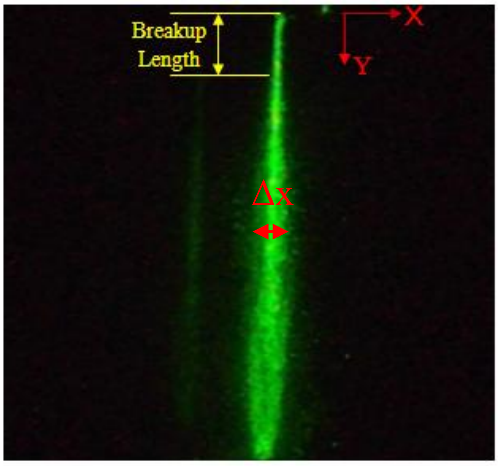

Figure 6 Laser image indicating break up length and Δx for high pressure case.

This Δx if plotted against the axial distance y will increase gradually at the beginning followed by a steep increase when the droplets tend to shear off from the edges. This transition zone is where breakup occurs and hence an estimation of the jet breakup length is obtained. A sample such Δx-y plot is shown in Figure 7. As can be seen, the initial gradual rise of the value of Δx can be linear fitted, followed by a sharp increase, linear fitting of which requires another straight line. This transition provides an estimate of the breakup length. To avoid any discrepancy, the intersection of these two linear fits is defined as the jet breakup length (L_b). Also, noteworthy in Figure 7, is the ordinate named as mean Δx. This mean value at a particular axial position is calculated based on all the images obtained at a particular pressure. Hence, for a particular y_i,

$$(\vartriangle x)_{mean} = \frac{1}{l}\sum_{1}^{l}(\vartriangle x)_l$$, where l = number of images at a particular pressure.

Plotting the mean also provides a smoothening effect to the data facilitating elimination of the unnecessary noise. The error in measurement of the breakup length (e) at a particular pressure is calculated as:

$$e_i = (\vartriangle x)_{mean} - (\vartriangle x)_i \qquad i=1(1)\ l \text{ such that}$$

$$e = \max(e_i)$$

where all the Δx *s* are calculated at *y= breakup length.*

The error magnitude thus calculated is less than 4 % for kerosene and less than 3 % for diesel and the biodiesel.

Difference in Low Pressure

In the case of low pressure injection (~10 bar), the above definition of droplet shedding from the edges fails as the breakup mode is found to be somewhat different. Instead, a ligament is formed at the onset of injection which after going downstream leads to a reduction in sheet thickness finally leading to breakup of the ligament. The distance of the axial position of this point from the nozzle exit is termed as the breakup length.

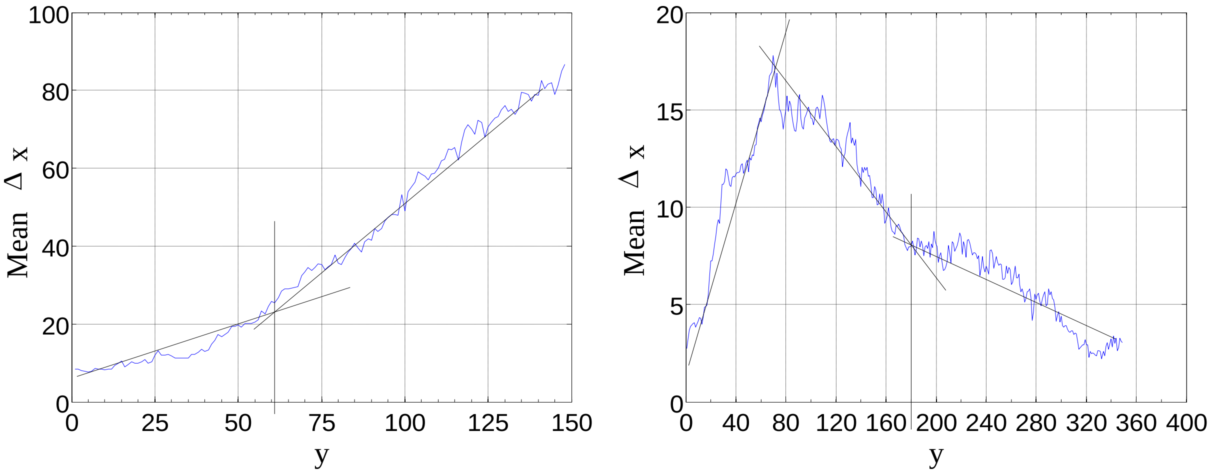

Figure 7 Mean Δx-y plot for diesel at a) 130 bar (left) and b) 10 bar (right).

Two variations of the above algorithm were used for these low pressure conditions:

I. While computing the I_{peak} at each axial position (y_i), a check is added such that if $I_{peak} < I_{crit}$, that axial position will be termed as the breakup length (L_b).

II. Instead of adding this check statement in the algorithm, if we plot the same mean Δx-y plot as explained earlier, a figure as explained in Figure 7 (b) is obtained. Unlike the high pressure case (Figure 7a) the plot of diesel at 10 bar shows an increase followed by a decrease in the Δx value. At some y_i, the sharp fall of Δx ceases followed by a gradual steady drop of the same. Comparing this with the laser photograph shown in Figure 8, this transition zone from sharp fall to a gradual drop in Δx is termed as the breakup length.

Consistency is obtained between these two low pressure methods. The variation in estimation of the breakup length using these two methods turned out to be around 3%, establishing the suitability of both of them.

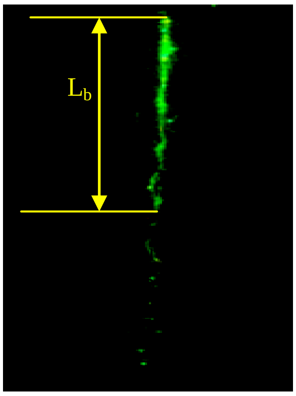

Figure 8 Laser image indicating break up length for low pressure case.

Droplet/Velocity Distribution

A spray characteristic study is incomplete without knowledge about the droplet size distribution and velocity field at nozzle exit. Measurements at the near nozzle zone still remain a challenging problem. We employ a Phase Doppler Particle Analyzer (PDPA) for measurement of the droplet size and velocity at a distance y=30 mm downstream of the nozzle tip.

The present work has been done using a two component PDPA (Model - Coherent Innova 70C from TSI, USA). A detailed description of the technique can be found elsewhere [37]. Briefly, the laser beam from an Argon ion laser was split into two components green and blue and made to pass through a Bragg cell which produced a 40 MHz frequency shift for each beam. These beams were then transported through fiber optics to the experimental setup where they intersect, which is the measurement point. Light scattered from the droplets crossing through the beams' intersection was acquired by the receiver and processed by the photo detectors.

Results and Discussion

In this section, we provide results of the spray characteristics obtained from the experiments. With increase in pressure/viscosity, the parameters showed expected variations. Also the trends are consistent with available literature [18; 38].

Figure 9 (left) shows the effect of injection pressure on spray cone angle, as calculated from light shadowgraphy technique. It can be clearly understood that with increase in injection pressure, spray cone angle also increases. Also compared is the effect of liquid fuel viscosity. At a given pressure, the least viscous liquid produces a wider spray cone angle than the others. This result is in good agreement with trends observed in literature. Another noticeable point is the similar nature of the curves, which suggests fuel flexibility of the injector. Uncertainty in measurement of spray cone angle lies within ±3 degrees from the mean value.

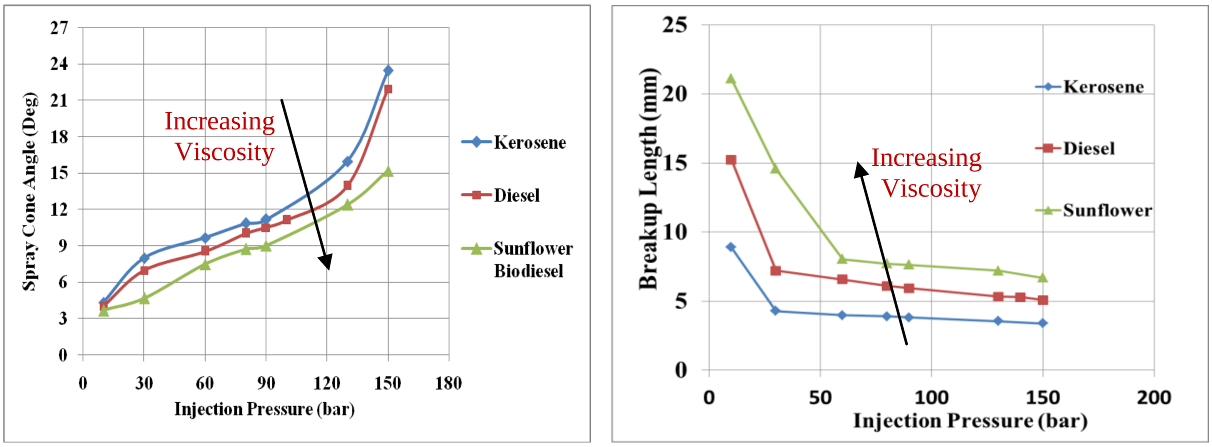

Figure 9 Influence of Injection pressure on spray cone angle (left) and breakup length (right) for different liquid fuels.

The spray cone angle was also estimated from the patternation studies using simple trigonometric relations. It was seen that the results showed consistency with those obtained from shadowgraph images.

Response of injection pressure and liquid viscosity on spray break up length is just contrary to that for spray cone angle. For a definite injection pressure, the most viscous liquid remains stable for a considerable amount of time thus breaking up at a longer distance from the nozzle tip as compared to the others (Refer to Figure 9 (right)). Similarity of the nature of curves again confirms to the fact that spray distribution is independent of liquid properties. As discussed earlier, the range of error was quite acceptable.

The diameter used to characterize the sprays is Sauter mean diameter (**D_{32}**) defined as:

$$D_{32} = \frac{\sum_{i=1}^{N} n_i d_i^3}{\sum_{i=1}^{N} n_i d_i^2}$$

where n_i is the number of measurements in the size range corresponding to the droplet diameter d_i and N is the number of ranges.

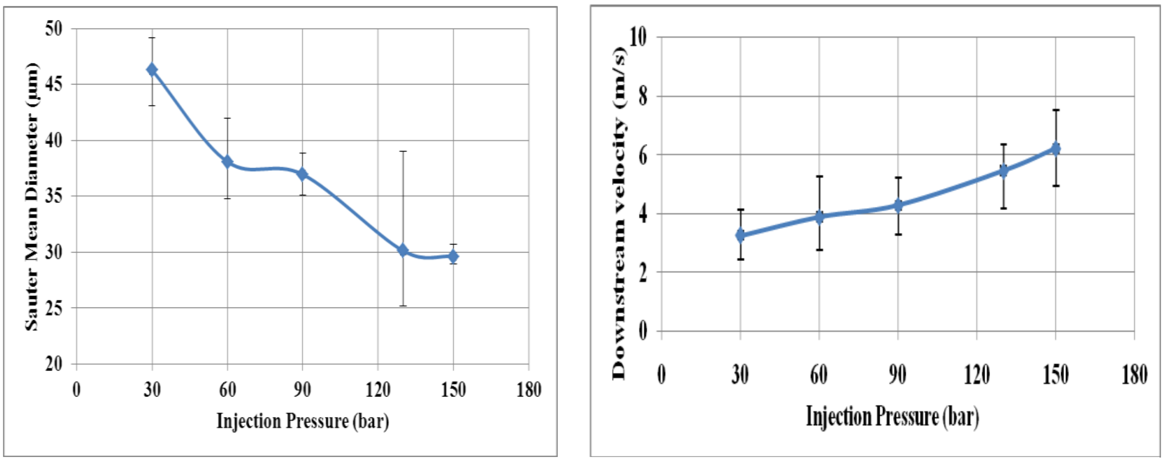

Figure 10 Variation of SMD (**D_{32}**) (left) and Downstream flow velocity (right) with Injection pressure.

A droplet size distribution was used by Mansour et. al [30] to show that the central droplets of the spray are smaller and hence accelerated at a much faster rate than the large droplets in the peripheral region. Hence, the central droplets being a crucial and characteristic parameter for atomization are being analysed for droplet diameter and velocity with variation of injection pressure (Figure 10). As expected in a spring loaded nozzle, the SMD is seen to decrease with injection pressure. The larger droplets having a lower response time show a lower velocity and vice versa. The error bars represent the maximum and minimum values for SMD and downstream velocity obtained at a particular injection pressure.

Summary and Conclusions

An experimental investigation of spray characteristics from a commercially available single orifice diesel injector was carried out at much lower injection pressure regime than those normally prevalent. Effects of injection pressure and liquid viscosity were investigated. Spray cone angle was evaluated by shadowgraphy technique and verified by volume based patternation studies whereas spray break up length was estimated by processing images using an innovative image processing algorithm in Matlab. Droplet size and velocity were obtained by Doppler principle using PDPA. The cone angle increased with injection pressure and decreased with viscosity. As expected, higher viscous fluids tend to remain stable for a longer distance downstream of the nozzle exit and hence possess a higher breakup length. Apart from usage of PDPA, measurement methods of spray cone angle and breakup length described herewith are cost effective and do not require any sophisticated instrument.

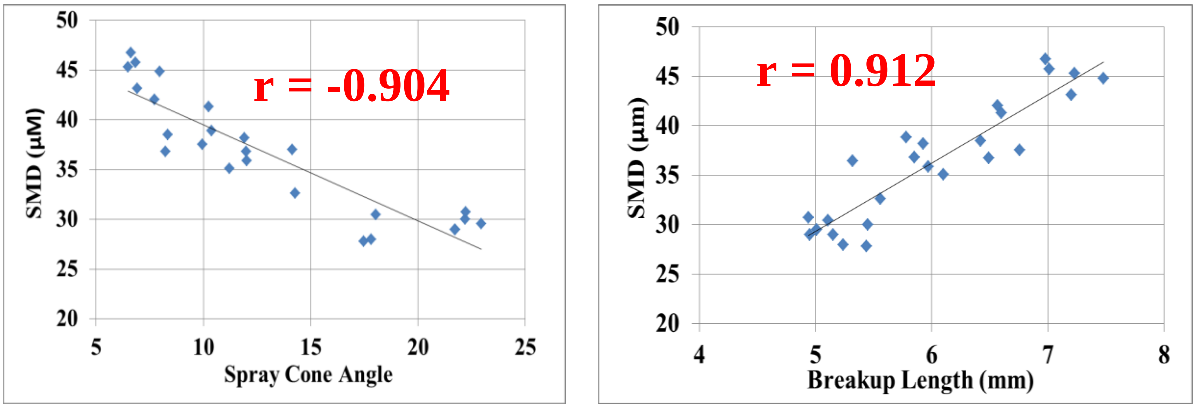

Figure 11 Good Correlation is observed among the parameters measured (r is correlation coefficient).

A high correlation is expected to exist among the parameters studied in this work. With increase in injection pressure, the droplet diameter decreases whereas the spray cone angle increases; hence a negative correlation is expected between the latter two. Reverse phenomenon is expected between the breakup length and the droplet diameter.

Owing to the immense applications of atomization, spray characteristics continue to be a celebrated topic of research. Using simple experimental techniques, we have performed a comprehensive study of three different fuels of varying viscosity. Also noteworthy, a wide range of injection pressure has been covered in the experiments. Hence, for other complex atomizers with the presence of airblast/pressure swirl, the spray properties can be characterized using these reported techniques.

Acknowledgements

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