SPRAY CHARACTERISTICS UNDER MUTIPLE INJECTION STRATEGIES OF BIOFUELS

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Abstract

The worldwide shortage of fossil fuels and emission norms in the automotive industry has increase the interest of people to make more efficient and effective engine. In order to make engine which follow the emission norms people increased their interest toward the alternative biofuels such as ethanol, methanol, biodiesel and many more. Biofuels have a capability to reduce NOx, soot formation and particulate matter (PM). By considering these it important to know the spray characteristics of biofuels under many injection strategies such main injection, pilot injection and split injection strategies. Before this it is important know that how spray characteristics affect the engine performance, emission and combustion characteristics. There are basically two types of spray characteristics that is macroscopic and microscopic spray characteristics. Macroscopic characteristics generally focuses on the macroscopic parameters of the spray plume such as spray jet penetration length, spray cone length, spray radial length and spray area. Whereas microscopic spray characteristics focuses on the microscopic parameters such as spray droplet size, binned spray velocity and average Sauter Mean Diameter (SMD). There are various experimental methods which is used to studies the spray characteristics. Macroscopic spray characteristics are easy to measure and cost effective whereas microscopic characteristics are quite expensive and sensitive to measure. After studying these characteristics, it is important to know that how multiple injection strategies affect the engine performance and combustion characteristics.

1. Introduction

Spray characteristics play a significant role in the engine performance, emission and combustion characteristics. So, it is important to study about the spray characteristics in detail. This review focuses on the spray characteristics of biofuels. The biofuels have different fuel properties such as viscosity, surface tension, cetane number, density and calorific value which will influence spray characteristics of these fuels. Experimental studies shows that these fuels have higher viscosity which can reduced their spray atomization quality and lead to incomplete combustion. Thus, the quality of spray atomization mainly depends on fuel injection system.

There are two class of characteristics the first one is macroscopic in which we study the parameters such as penetration length, spray cone angle and spray radial width. These parameters can be determined by high-speed camera and image processing technique (MATLAB code). Second class is microscopic characteristics such as spray droplet and SMD. These parameters can be obtained by Particle Image Velocimetry (PIV), Phase Doppler Particle Anemometry (PDPA) and Laser Induced Fluorescence (LIF).

According to many studies and experiments the spray behaviour depends on the fuel temperature, initial cylinder pressure, fuel injection pressure (FIP) and cylinder pressure. However, the amount of NOX emission from biofuels can be reduced by using injection strategies such as late or early injection. Various studies also shows that the multiple injection strategies such as injection timing, interval between injections effect the emission spectra NOX and many other pollutants.

2. Detailed overview of both characteristics

As spray characteristics is plays a crucial role in engine performance and the emission released by an engine. Thus, it is important to know how these properties measured experimentally and how physical condition such as pressure, temperature affect these properties. It is also important to study how the parameters which is in our control such as fuel injection pressure (FIP), ambient chamber pressure, injection timing and injection angle affect the geometry of spray.

First, we look at the both the microscopic and macroscopic spray characteristics. Then study about how multiple injection strategies affect the engine performance and its emission and combustion characteristics.

2.1 Experimental setup of macroscopic spray characteristics

In this experiment generally there is one chamber which is filled with nitrogen at medium pressure and high temperature. This chamber is generally known as constant volume combustion chamber (CVCC) or constant volume vessel (CVV). The vessel is made up of high-quality alloy which can survive at extreme condition of 100 bar pressure and 1000K temperature. On this chamber the solenoid injector is placed normally to it which is connected to the common rail injection system. The fuel injection system is containing high pressure fuel pump which have highly pressurized fuel of 1800 bar. The fuel injector injects the fuel at various FIPs and this spray plume illuminated by the light source. Due to this light it easier for high-speed camera to capture clear images of spray and then these images is further processed by image processing technique.

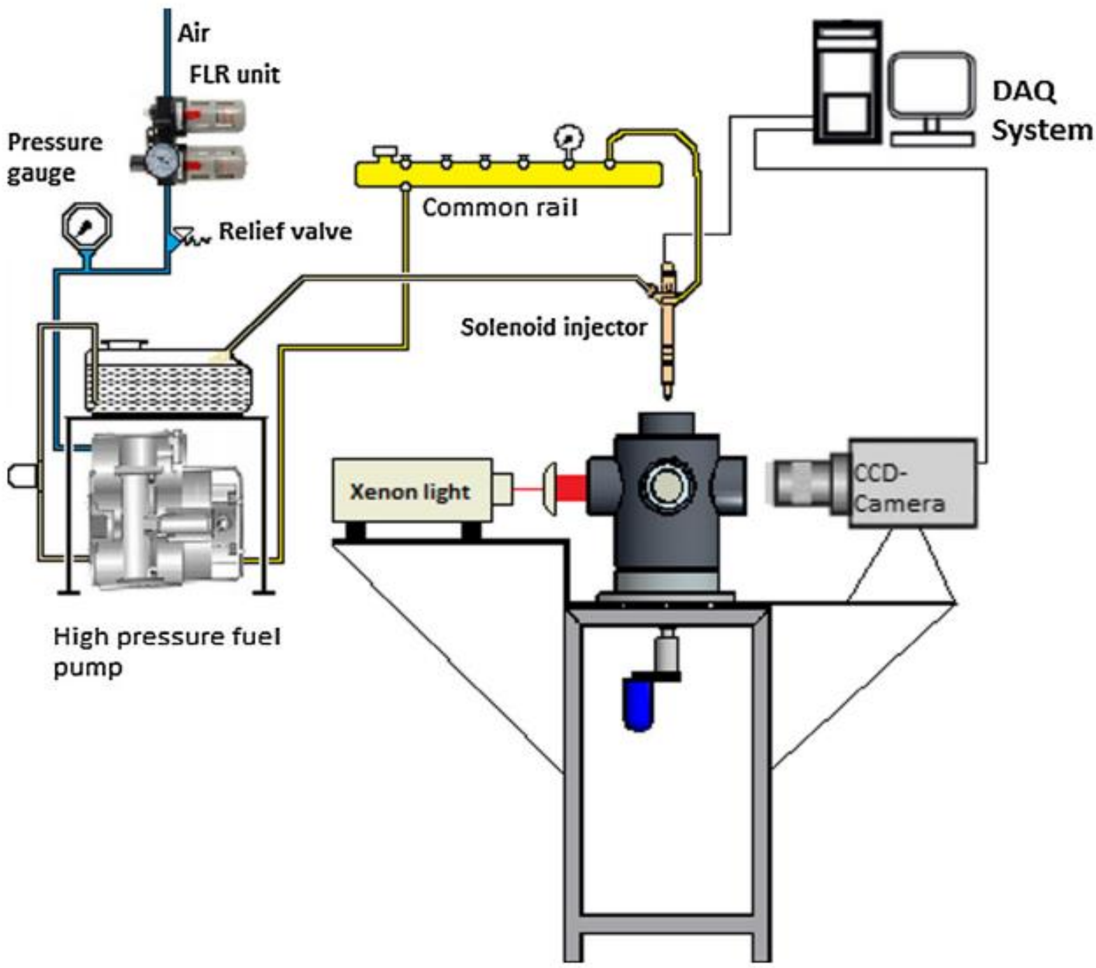


Figure 1. Experimental setup of constant volume vessels

The setup shown above in figure 1 clearly shows the each and every component clear which helps to understand the basic principle of experiment.

Then after by capturing all the images at desired physical condition separate sets of images are created. Then the MATLAB code is generated which help to process the images. The basic theme of that MATLAB code is that from the set of let's say 180 images the first image without injection is taken as background or reference image. Then this reference image is subtracted from the other images to remove background of an injected image. Then this image is binarized with the help of by choosing suitable thresholding value whose range is 0 to 255 generally its value is between 7 to 15. Depending on different FIPs and ambient pressure these threshold values is changing. The image is cropped and focus on the area of interest in an image. There is several function MATLAB such as bwareaopen, imclose, imfill and median filter were used to effectively reduced the noise. After that final binarized image is obtained and then with the help of several function were used to find various parameters such as spray penetration length, spray cone angle, spray area and spray radial length.

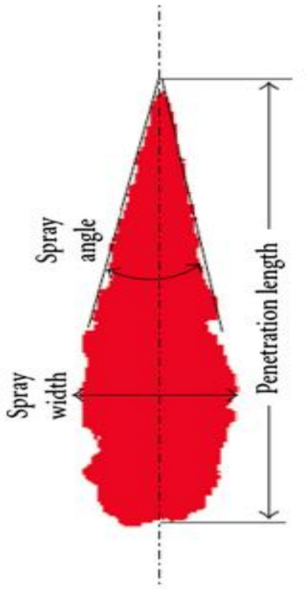


Figure 2. Measurement of macroscopic spray

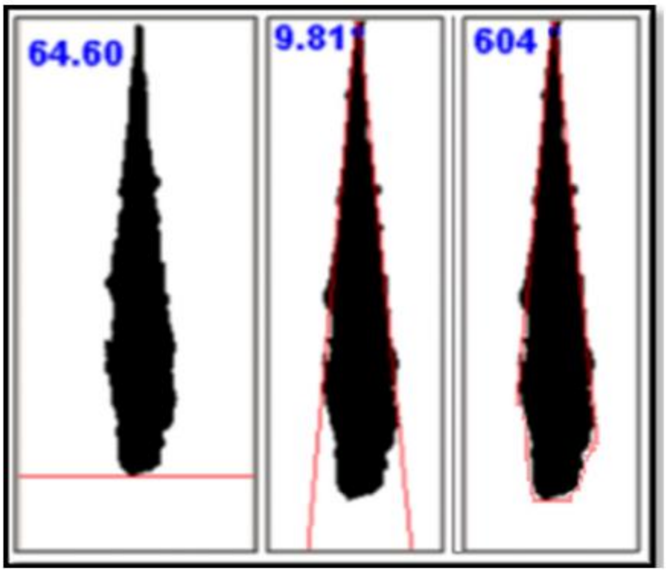


Figure 3. Annotated spray measurements

Thus, the above figure 2 shows the three main parameter penetration length, spray cone angle and spray radial width. These, parameter measured by the MATLAB code. The spray penetration length is defined as the distance between injector nozzle and far point of spray from that nozzle whereas cone angle is defined by the angle formed by tangential lines which touches the outer periphery of an spray, and radial width is the maximum horizontal distance between the periphery of an spray.

2.2 Effect of injection strategies on macroscopic characteristics

As macroscopic characteristics is playing a crucial role in engine performance. But it is affected by the injection strategies used during injection of fuel. In this we see the effect of pilot injection and main injection on penetration length of different biofuels. In these injection strategies fuel is injected at two different timings. Firstly, the fuel is injected 5-to-10-degree crankshaft before the main injection. These injection strategies are an effective way to reduce ignition delay. In pilot injection the quantity of first fuel injection is very less that the quantity of main fuel injection whereas in the split injection the quantity of both the fuel injection in this case is same.

Various studies and experiments were conducted how these two strategies affect the spray penetration length of different biofuels. As shown in figure 4 each vertical bars shows the spray penetration length for different biofuels such as RME, TME, CME, SME, WCME and ULSD. Figure 4a shows the comparison of spray penetration length of pilot injection at 0.53ms and 0.60ms after the command to start pilot injection whereas in figure 4b shows the comparison between penetration length at main injection strategy measured at different timings. The grey bar of ULSD taken as a reference bar and variation of penetration length compared from ULSD for both pilot and main injection.

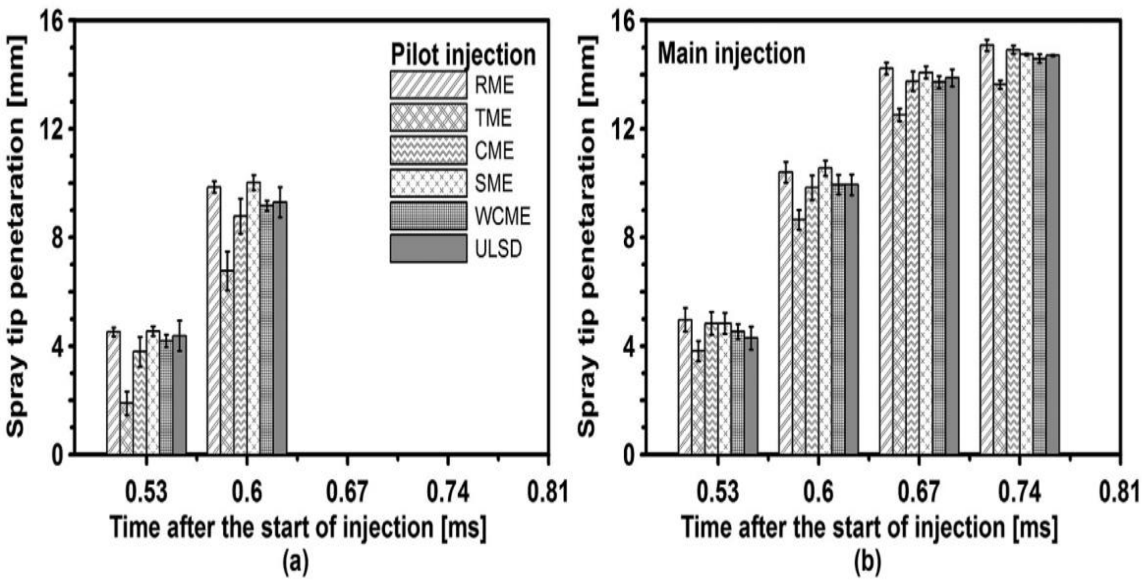


Figure 4. Spray Penetration length at different timing for pilot and main injection

As we can seen the figure that the penetration length of RME and SME are both comparable to each other and they both are slightly longer than the ULSD whereas as TME has the lowest spray penetration length among all of the biofuels. TME has lowest penetration length in both pilot as well as in the main injection. The differences in the TME and ULSD as well as all other fuels is due to the differences in the flow properties of fuel through nozzle hole caused by its high viscosity. This viscosity causes the delay in the early start of injection because it affects nozzle needle move during the initial opening. Due to this effect TME is decelerate its injection speed and result in the small penetration length in pilot injection whereas in main injection it again has lowest value of penetration length among all fuels but the relative difference in this case quite small. Because in main injection needle is fully lifted and TME spreads up very easily due to plenty of time whereas in pilot injection relative difference is large due to limited time of injection.

Till now we seen only for the penetration length now we see for spray cone angle and spray area variation for different biofuels. As shown in figure 5 the variation of cone angle for different biofuels same as in case of penetration length are used to see the variation of spray angle at different injection timing for pilot and main injection. It can be seen in the figure 5a for pilot injection the average cone angle values of all biofuels is lower than ULSD for main injection also the average cone angle value of all fuels is lower than ULSD in this case also ULSD is taken as the reference fuel.

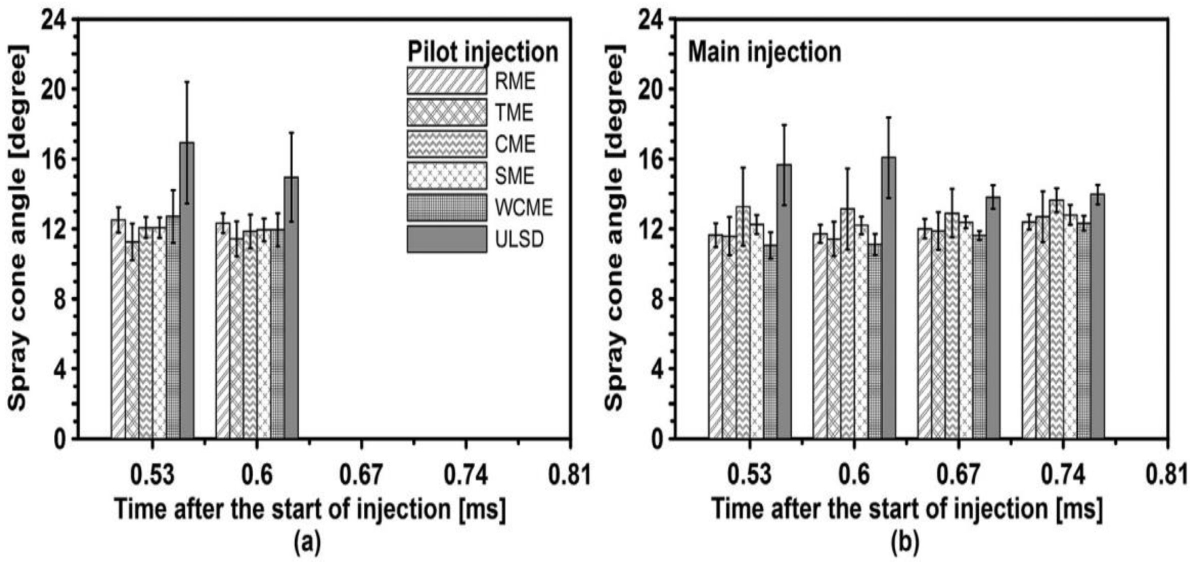


Figure 5. Spray Cone angle at different timing for pilot and main injection

Thus, from figure 5 it can be easily seen that the spray cone angle for both pilot and main injection the spray cone angle for all biofuels is lower than the ULSD. And the difference in the cone angle from ULSD is decreases from pilot to main injection. The difference is decreased due to the increased in the injection duration. In general small cone angle value of all biofuels is due to the higher viscosity and density which causes the poor atomization of fuel in compare to ULSD due to which spray cone angle is smaller than ULSD.

Now we seen the spray area variation of these same biofuels for pilot and main injection. As shown in figure 6 it also shown the spray area at different injection timing of different biofuels for pilot and main injection.

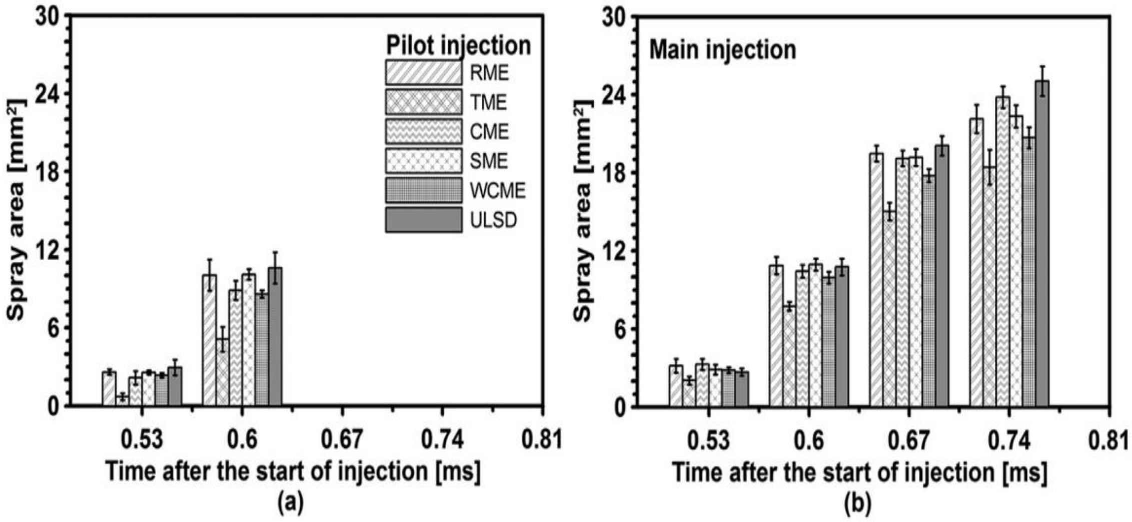


Figure 6. Spray area at different timing for pilot and main injection

From figure 6a it can be easily seen that the for pilot injection spray area of RME, CME, SME and WCME is lower than ULSD whereas for TME is extremely lower than other biodiesels for both pilot and main injection. The difference in the spray area of TME and ULSD is larger for pilot injection in comparison to main injection. For main injection the spray area of RME, CME, SME and WCME was higher than ULSD.

As spray area is the important parameter which determine the strength of air-fuel mixture in the combustion chamber. Increase in spray area result in the more distributed air fuel mixture which helps to complete the combustion completely and effectively. In this case also the variation of biodiesel from ULSD is attributes towards its physical properties such high density and viscosity which result in the small spray area.

Till now we have discussed the effect of injection strategies on the macroscopic characteristics of the biofuels by using main and pilot injection. It shows that how the spray penetration length, spray cone angle and spray area affected by physical properties of fuel such as high density, high viscosity affect these parameters in case of pilot and main injection.

2.3 Brief Overview of Microscopic spray characteristics

Microscopic spray characteristics mainly focuses on the property of spray droplet in a spray at very small scale. Microscopic characteristics describe mainly spray droplet size, component of radial and axial component of velocity of droplets, droplet number density and droplet size distribution. Spray droplet can be measured by various diameter such as volume mean diameter, arithmetic mean diameter and sauter mean diameter (SMD).

Volume Mean Diameter – It is defined as the diameter of droplet that gives the volume of complete sample, if multiplied by the total number of droplets.

Arithmetic Mean Diameter – It is the average of all the diameter of spray droplet in a plume.

Sauter Mean Diameter (SMD) – Sauter Mean Diameter is the average measure of particle size. It is defined as the diameter that has same volume/surface area ratio as particle of interest.

2.4 Experimental setup of microscopic spray characteristics

This experiment consist of ambient chamber pressure condition in constant volume spray chamber (CVSC) in which non reacting gases are filled with high pressure. This CVSC consists of seven flanges out of which five flanges has quartz window and remaining two have metallic window. Ou of these two flanges one flange is connected on the top of CVSC which hold the injector and other metal flange is at the bottom which support the drain valve for continuous air purge from the CVSC.

This CVSC experiment consist of the fuel injection system, CVSC and phase Doppler interferometry (PDI). And each of this system consist of several component. First focus on the PDI system the Artium 3D system consist of two transmitters, one receiver, three signal analyzers and a computer. These two transmitters delivered the six-laser beam, which is intersected in point called probe volume. This PDI instrument help to measure the droplet size and velocity distribution and also measure the drop size and one component of velocity. A second pair of laser beams disposed orthogonal to the first pair is used to measure the orthogonal velocity component. Hence, the droplet size and two components of droplet velocity are measured simultaneously. The diameter is measured for every droplet. The diameter measured is orthogonal to the plane of the respective laser beams performing the measurements.

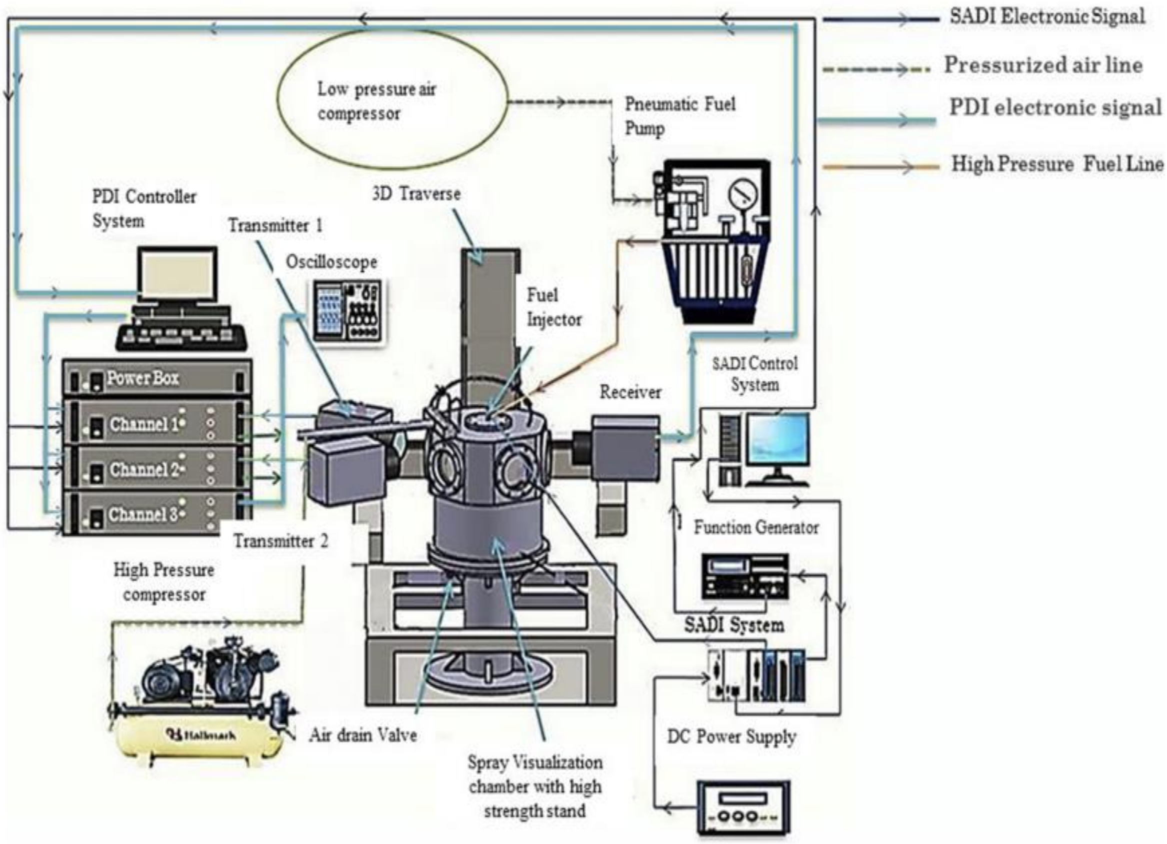


Figure 7. Schematics of CVSC for microscopic characteristics measurement

As shown in the figure 7 it is very clear from diagram that how each component of experiment connected to each other. In this experiment, there are four lasers beams of different colours. These beams are converge together to form one spot in the CVSC. This convergence of a beams is done on the quartz window, which is transparent to these laser beams and at the same time another quartz window is setup to receive the signal which was captured by PDI receiver. The receiver and transmitter are positioned in such a way that that the angle between them is 30 degrees. Both the transmitter and the receiver were mounted on a device that allowed them to move in three dimensions. There is one high speed camera which is used to visualize the spray evolution. It is used to see what was actually happening in the setup. The minimum frame rate of 5400 fps at maximum resolution and minimum resolution of 675000fps which means that this camera capture the images very quickly help to provide more relevant information. The ability to capture the image very quickly allow the researchers and experimentalist to visualize the spray evolution in more detail and also study them in more deeply which help them to achieve the better result in great detail. The high speed is also very essential in the measurement of macroscopic spray characteristics.

2.5 Detailed overview of microscopic spray characteristics

As we know that microscopic characteristics deals with the small scale region of spray such as droplet diameter, velocity distribution and component. The atomization is a process in which fuel is atomizes in a very fine droplets compared to the injector nozzle size. The degree atomization influences the air-fuel mixer in the chamber which effect their emission spectra and engine performance. Thus, it is essential to study microscopic characteristics. This review is mainly focuses on Sauter Mean Diameter (SMD) and spray droplet diameter.

a). Sauter Mean Diameter (SMD) – It is defined as the diameter of a drop having the same volume/surface area ratio as the entire spray. SMD is a collection of spherical objects of different sizes is equal to the diameter of a collection of spherical objects forming a collection. SMD is especially important in calculations where active surface area is important to study.

b). Spray Droplet Size – It is referred to the size of liquid droplets that are emitted from spray nozzle. Droplet size is essential in determining the effectiveness and efficiency of spraying process. The size of spray droplets depends on many factors such as types of nozzles, pressure of fuel injected, viscosity and surface tension of a fuel, and environmental condition or combustion chamber condition such as ambient temperature, pressure and humidity.

These parameters which are stated above are essential to know the effectiveness and efficiency of a spray atomization. Atomization affects the ignition quality and combustion efficiency of a fuel. Several experiments and studies show that when the spray velocity is too low, droplets size become larger than nozzle hole and making the combustion of a fuel inefficient whereas high velocity of spray injection helps to break up the fuel into small droplet which easily mixes with the air to improve efficiency of combustion. The vaporization of the fuel is also playing a crucial role for combustion quality. Several studies shows that the ambient conditions like temperature and pressure and the fuel temperature affect the vaporization of a fuel which directly affect the combustion efficiency of a fuel.

Therefore, it is crucial to understand the microscopic characteristics of a fuel in order to know the effectiveness and efficiency of a fuel atomization.

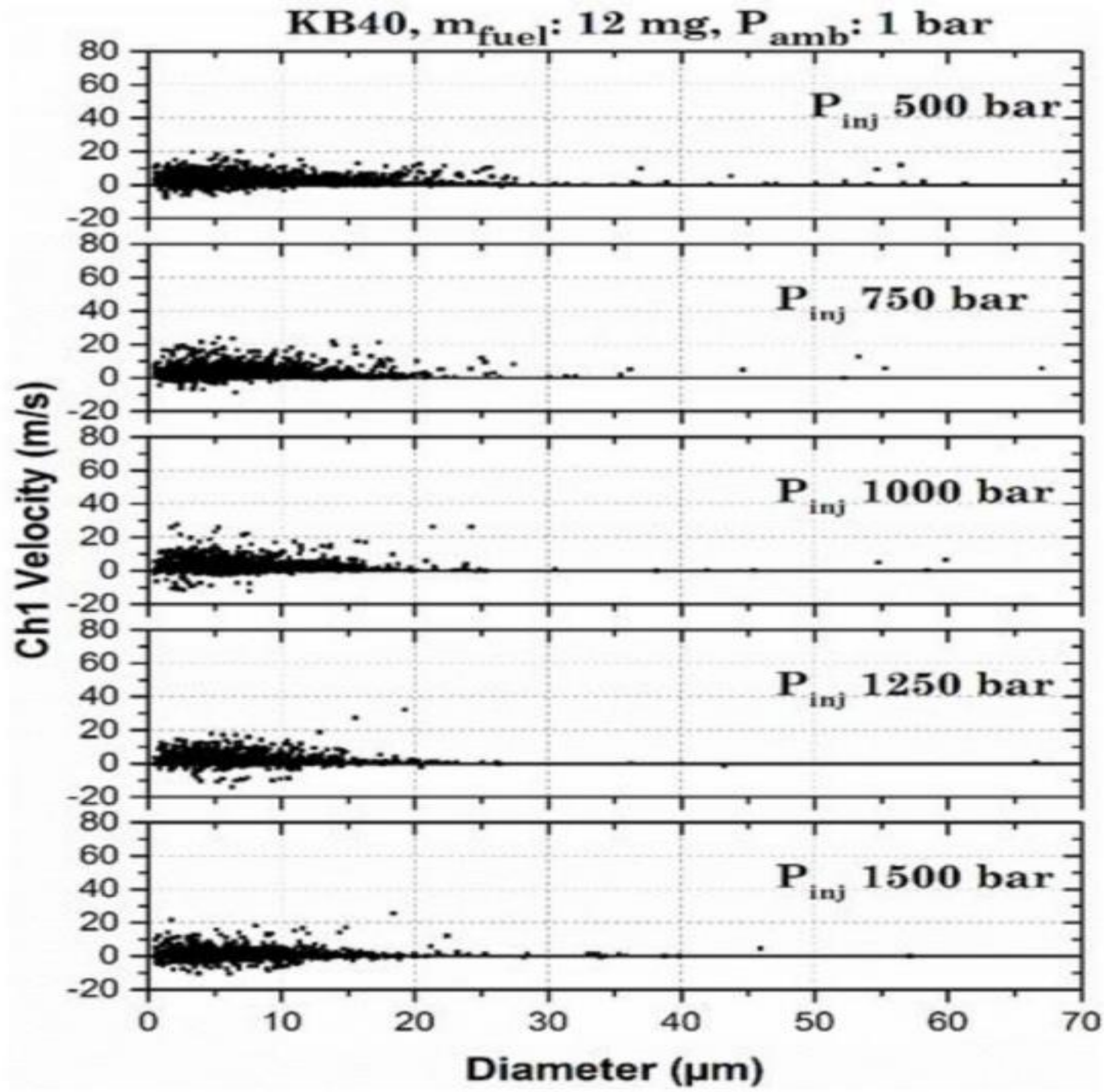
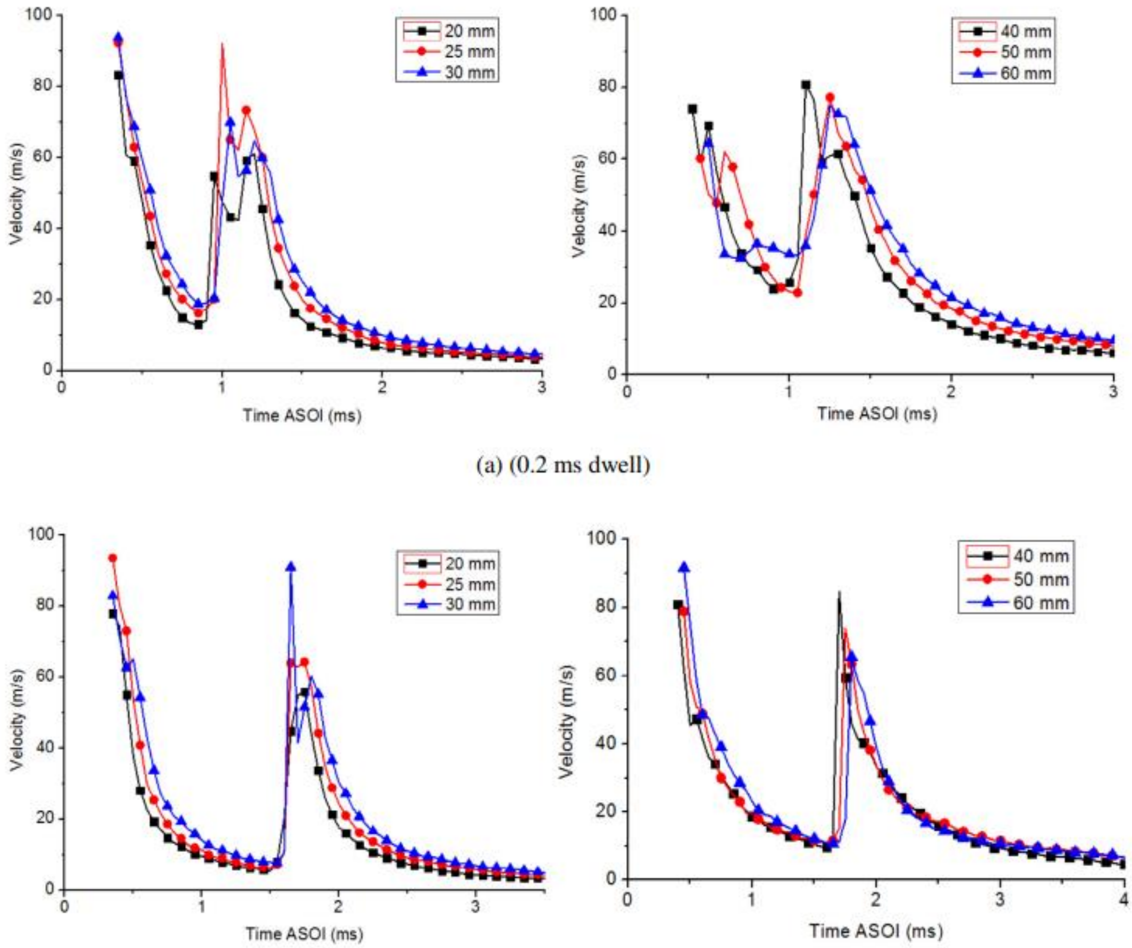


Figure 8. Scatter plot of droplet diameter and axial velocity

As shown in the figure 8 it represents the scatter plot of spray droplet size in X axis with axial component of velocity at Y axis. This figure indicates the diameter to velocity correlation of spray droplet of blend Karanja biodiesel of 40% blend (KB40) at different fuel injection pressure (FIP). In this figure each point represent the measurement of droplet size and speed. When the spray start coming out from the nozzle it can be observed that outer droplets break up faster in comparison to inner droplet part due to rapid movement of outer periphery of fuel spray. This figure also indicates that by increasing fuel injection pressure (FIP) increases the droplet peak velocity. But at 1500 bar peak velocity is observed to lower due to the poor atomization of fuel. Peak velocity distribution of smaller droplet size was higher for mineral diesel in compared to blend biodiesel (KB20 and KB40) whereas for large droplet size blend biodiesel shows high peak velocity in compared to mineral diesel.

So far, we discussed the effect of FIP in spray droplet size and velocity distribution. Now we see the effect of split injection technique in the mean velocity of spray droplet with different dwell timing. Dwell is the time interval between two consecutive injection of fuel.



(a) (0.2 ms dwell)

(b) (0.8ms dwell)

Figure 9. Mean velocity at various position at different dwells

As shown in the figure 9 which indicates the average velocity at two different dwells (0.2ms and 0.8ms) at 60Mpa injection pressure. As we see almost all the curve at 60Mpa shows the similar trends. Initially the velocity is sharply decreasing and then it start quickly rising just before second injection takes place. From figure it is also observe that the peak velocity at second injection for 0.8ms dwell is lower than the peak velocity of first injection whereas for 0.2ms dwell the peak velocity of first injection is lower than second injection. The main reason behind this is the dwell timing (time interval between injections). As the injection duration decreases, the high velocity phase during the second injection event become longer. This happens because the shorter dwell time cause the injector to open for long period of time during the second injection, due to which more fuel being injected at a high velocity. Hence, the shorter pauses between injections result in the injector to open for long time period and causing more fuel to inject at a very high speed.

Now we see the effect of dwell on the velocity at 60 MPa fuel injection pressure.

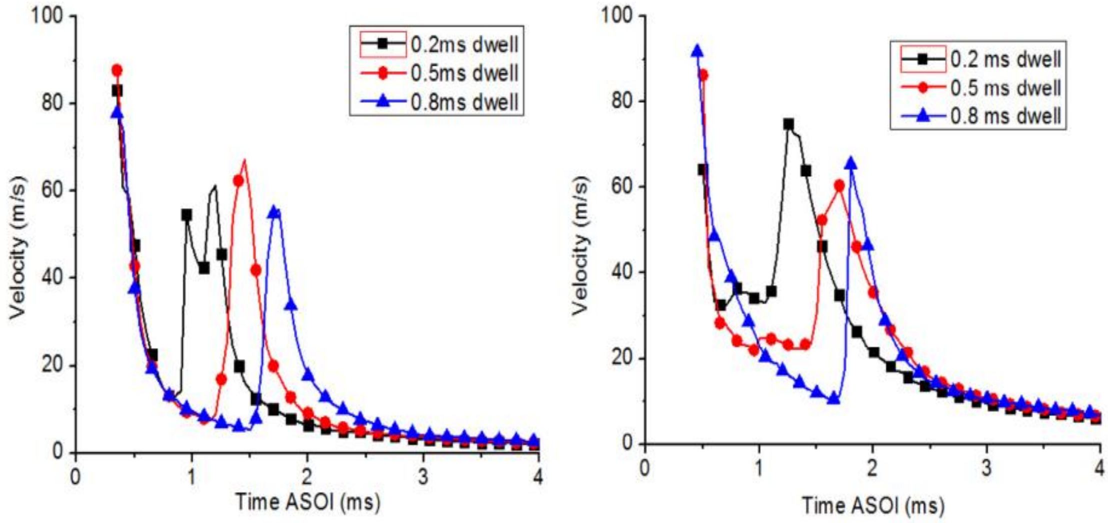


Figure 10. Mean velocity comparison of 2 split with various dwell under 60 MPa

This figure indicates that the injection dwell has less affect on the velocity of the first injection event but it influences the velocity of second injection event especially at 20 mm and 60 mm away from the injection. At 60 MPa pressure, the case with 0.5ms dwell time at 20mm distance from the injector shows the highest peak velocity for the second injector event. While on the other hand we can easily seen that the with 60 mm position from the injector, the case with 0.2ms dwell time present the highest peak velocity in comparison to second injection event.

In simple words, the between the injection that is dwell timing does not affect the speed pf the first injection so much but the impact is observable at second injection event, especially for specific distance from the injector that is 20 mm and 60 mm. This figure 10 shows the that shorter dwell timing led to the high velocity during second injection event, depending on the distance from the injector.

3. Multiple Injection Strategies

There are mainly two types of multiple injection strategies such as pilot injection and split injection. In these strategies the fuel is injected at two different timings. Firstly, the fuel is injected 5-to-10-degree crankshaft before the main injection. These injection strategies are an effective way to reduce ignition delay. In pilot injection the quantity of first fuel injection is very less that the quantity of main fuel injection whereas in the split injection the quantity of both the fuel injection in this case is same.

3.1 Effect on spray characteristics under pilot injection

Many studies and experiments show that the pilot injection affect the spray characteristics up to great extent. As show in the figure 11 it shows the effect of pilot injection on spray penetration length. There are a three test cases with different timing interval of first and second injection. In first injection there is a similar penetration length irrespective of the interval of injection timing. And the second injection developed more quickly than first due to increase in momentum of a spray particle than first one. From figure it is also conclude that when there is longer time interval between injection then the spray development is slow down. This because the gas flow generated by the first injection weaken the effect of second injection and the first injection particle also collide with the second injection particle due to which the momentum of particle is reduced and spray development goes slow down.

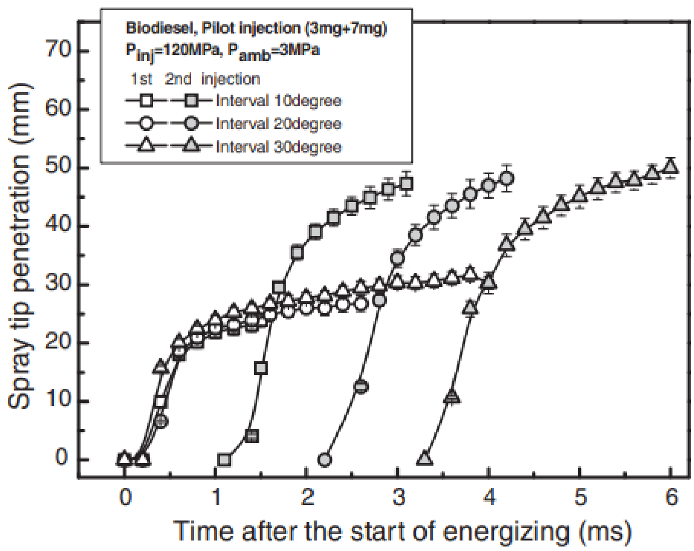


Figure 11. Spray characteristics using pilot injection

3.2 Effect on spray characteristics under split Injection

As shown in the figure 12 shows the effect of penetration length of a fuel under split injection. For first injection it shows the similar behaviour as in the case of pilot injection but due to large quantity of fuel in first injection in comparison to pilot first injection there is an increase in the penetration length of fuel at the later stage. Whereas for the second spray injection it shows the similar behaviour as in the case of pilot injection because in both injection strategy there is a same fuel quantity in the second injection.

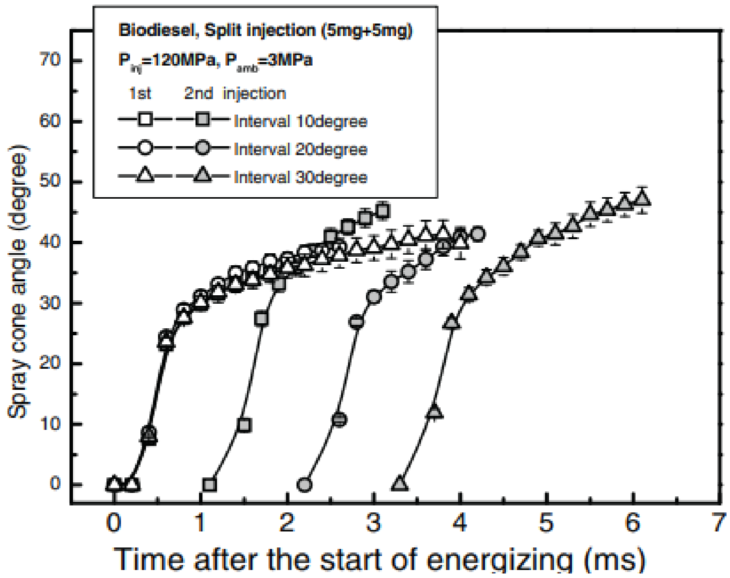


Figure 12. Spray characteristics using split injection

However, this review is highlighted by only one spray characteristics that is penetration length. There are many other parameters like spray cone angle, jet area, SMD which greatly affected by the injection strategy of the fuel.

4. Summary

This literature review summarizes and conclude that the spray characteristics of fuel have a great effect on the combustion and ignition quality of a fuel due to which desired emission norms can be reached. By understanding the spray behaviour help or give the possible solution to reduce fuel consumption and pollution emission levels. Both microscopic and macroscopic characteristics of a spray is depended on the fuel properties such as viscosity, vaporization and surface tension. These properties also affect he atomization of fuel spray which create problem to atomizes the fuel spray and lead to the inefficient air fuel mixer. As stated above macroscopic properties of fuel is easy to detect which include high speed camera, white light falls on the spray and the image processing technique (MATLAB code) help to measure the characteristics whereas microscopic characteristics like droplet size, Sauter Mean Diameter (SMD) were quite expensive and several techniques were used such as PIV, PDPA and LDV.

Multiple injection techniques such as pilot, main and split injection also have a great influence in the engine performance and combustion quality of fuel. These injection techniques affect the spray characteristics of a fuel and with depending on the need from the engine favourable injection technique were used in the engine for better spray characteristics.

Notations

CME – Coconut Oil Methyl Ester

RME – Rapeseed Methyl Ester

SME – Sunflower Oil Methyl Ester

TME – Tallow Methyl Ester

ULSD – Ultra- Low Sulphur Diesel

WCME – Waste Cooking Methyl Ester

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