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Study on Atomization and Spray Characteristics of Liquid Fuels in Co-flow Streams

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ABSTRACT

Spray atomization refers to the conversion of a bulk liquid into a collection of fine droplets (spray), typically occurring when a liquid passes through a nozzle. The atomization and spray processes constitute a gas–liquid two-phase flow of significant practical relevance in internal combustion (IC) engines. Laser diagnostic systems have emerged as powerful tools for investigating unsteady fluid mechanics. A major challenge in combustion research is the control of NOx emissions while maximizing efficiency and achieving favorable temperature distribution and other combustion-related physical phenomena. In the present work, experimental techniques such as Particle Image Velocimetry (PIV) and Particle Shadowgraphy are employed to determine velocity fields and droplet size distributions. From the droplet size distribution, relevant statistical parameters are obtained, among which the Sauter Mean Diameter (SMD) is particularly significant. Co-flow refers to the surrounding airflow introduced around the fuel spray using a cylindrical enclosure to minimize atmospheric disturbances and achieve a more uniform velocity field, enabling identification of optimal operating pressures. Furthermore, using SMD and other parameters, the penetration length of the fuel spray is analyzed. These parameters are measured using CCD cameras and optical diagnostic methods.

Keywords:-Non reacting spray, co-flow, spray cone angle, sauter mean diameter, particle image velocimetry, shadowgraph

1. INTRODUCTION

1.1 Energy and Combustion Devices

The internal combustion engines are spread to the extent that they represent the main cause of pollutant production. Nevertheless, it is well known that the stocks of fuels traditionally used in this kind of engines will be able to satisfy the world's needs for few more decades. Despite the large variety of alternate energy sources available, such as nuclear, solar, wind, hydroelectric, geothermal, and OTEC(ocean thermal energy conversion), chemical energy derived from burning fossil fuels supplies a disproportionately large fraction of the total world energy needs around 85 % at present.

1.2 Fuel Pollution and Health

Combustion needs fuel. Furthermore, the satisfactory operation of different heat and power engines usually depends critically on the compatibility of the fuel used. Examples are the unsuitability of diesel fuel for use in gasoline engines because it is relatively less volatile, and the narrow compositional specifications of gases which can be used in domestic gas stoves in order to maintain flame stabilization by avoiding blow off and flashback. The major pollutants from combustion are soot, SOx, NOx, unburned hydrocarbons (UHC), and carbon monoxide (CO). As just mentioned, soot is expected to be a serious problem with the burning of derived fuels and the large-scale deployment of high-compression engines such as the diesel.

1.3 Spray Fuel Characterization

Due to technological improvements it's possible in present times to characterize the injection fuel process in such conditions that match those happening when the engine is running under standard conditions, hence the purpose of these studies, which focus in the achievement of a perfect mixture between the working and active fluids; as a result of this, a series of consequences are triggered that lead to an optimum combustion, and therefore in the improvement of the engines capabilities. In diesel engines the combustion process basically depends on the fuel injected into the combustion chamber and its interaction with the air. The injection process is analyzed from this point of view, mainly using as basis the structure of the fuel spray in the combustion chamber, making this study of high importance for optimizing the injection process, and therefore reducing the pollutant emissions and improving the engines performance. The analysis of the liquid length penetration is very useful to determine the geometric design of high speed diesel engine combustion chambers with direct injection. [1, 2]

The diesel spray can be defined with the following physical parameters.
1. Spray tip penetration 2. Spray angle 3. Break up length

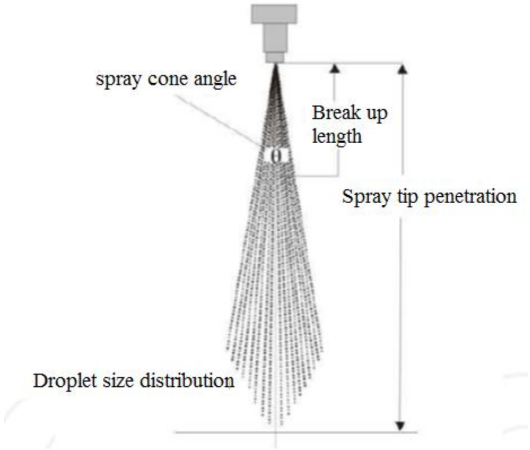


Fig. 0.1 Physical parameter of a diesel spray [1]

1.4 Laser Diagnostics System

We have number of techniques to measure velocity in the flow field but all these techniques require a sensor which has to be positioned in the flow field. As such, these procedures are prone to position error. Also the instrument will disturb the flow field and it will sense only a small region of flow field. And hence it is not possible to measure the instantaneous velocity field. Therefore a new technique was evolved which used laser and optical system to measure the velocity field by tracking the individual particle in the flow field. Following are some measurement techniques [3].

1. Particle Imaging Velocimetry
2. Optical Diagnostics
3. Laser Doppler Anemometry
4. Phase Doppler Anemometry
5. Planar laser Induced Fluorescence

2. LITERATURE SURVEY

2.1. In July 2015 Mayur J Sathe, Iqbal H. Thaker et al.

Studied the visualization about the flow structure. As already discussed PIV is one of the technique to measure the flow parameters. It is a technique to measure dispersed phase size, dispersed phase holdup and velocity of both the phases. The current work reports measurement of the shape, size, velocity and acceleration of bubbles using shadowgraphy, and liquid velocity measurement obtained using PIV/LIF with fluorescent tracer particles.

2.2. In June 2018 S.N. Soid, Z.A. Zainal

They also studied on spray and combustion characteristics using optical techniques in internal engines. Few experimental works have investigated the effects of modifications to the injector itself, for example, varying the injection rate, injection pressure, etc. In order to provide a better understanding of spray and combustion characteristics, researchers have studied macroscopic and microscopic parameters using optical techniques. The typical spray structure of a DI (direct-injection) fuel spray, where the fuel is introduced into the engine cylinder through a nozzle. As the liquid jet leaves the nozzle, it becomes turbulent and the outer surface of the jet breaks up into droplets.

2.3. In 2021 T. Berg, J. Deppe et.al.

Studied on spray and they compare the same results using different measurement technique. A detailed discussion of the results requires specific corrections of the data to compensate for the inherent effects of the different sampling methods, i.e. flux-sensitive and concentration dependent. He had applied all three measurement techniques (PDI, IMI and Shadow Imaging) are applied to analyze droplet diameters and velocities at three positions in the spray. Fig 2. shows the investigated areas of interest in the spray, i.e. at vertical distances of 40 mm, 70 mm and 100 mm from the nozzle, shifted 25 mm horizontally from the nozzle plane. Furthermore, the figure shows the global spray cone geometry from Mie scattering on the axis of symmetry, whereas the flow field is taken via Particle Image Velocimetry (PIV) of the droplets in the plane of measurement for droplet sizing [13].

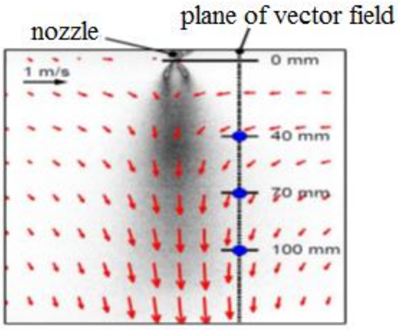


Fig. 0. Positions of measurement and flow field from PIV investigation

3. METHODOLOGY AND DESIGN

Laser Diagnostics system consists of:

a. Charge coupled device (CCD) camera.
b. Diffuser.
c. Double cavity laser.
d. Microscope

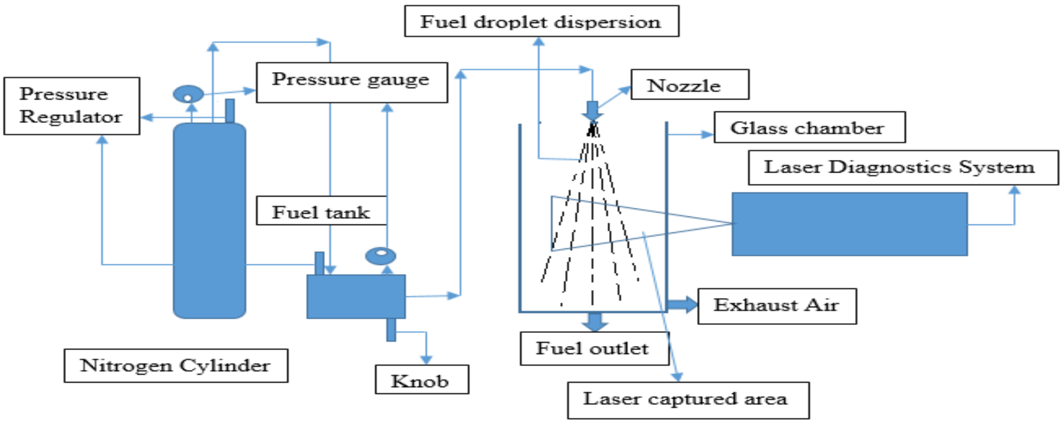


Fig. 0.1 Schematic Diagram of the Experimental Setup For atomization of fuel without co-flow

Fig 3.1 shows the schematic of experimental setup of without co flow condition. The setup consist of a nitrogen cylinder of capacity 47 liter in which the gas occupied volume is 7 cum. Fuel tank of capacity 14 liters , pressure gauges of various range, non-return valve, fuel nozzle from 1.87 kg/hr. to 7.22 kg/hr. A CCD camera imager pro sx 5m having resolution 2448 x 2050 pixel, an Nd: YAG double cavity laser, laser controller in which the coolant is their which need a temperature around 23-26 ^{0}c, diffuser light for shadowgraphy purpose, and at last a traversing system on which a fuel nozzle is mounted for proper location of fuel nozzle, it have a stepper motor due to which it is able to move the nozzle in X and Y direction with a fine accuracy. Also there is a glass chamber circulated around the nozzle to avoid the dispersion of fuel. The chamber also consist of a exhaust valve which is used to blow off the air, also in case of co flow, these valve is used to create suction to get uniform air velocity.

3.1 Components of experimental setup

1. Fuel tank and CCD Camera

Fig 3.2 shows the fuel tank and CCD camera. A pressure gauge is mounted on a fuel tank whose pressure range is up to 14 bars. It consist of 3 ports, one is for pouring the N_2 gas, another is for pouring the fuel and the last is for exhausting the air. With the help of this fuel tank, fuel is supplied to nozzle through flexible hoses. Another fig shows a CCD camera which is used to captured the images. The front of the camera is covered by filter while taking images of PIV to avoid the effect of the laser on camera. In case of shadowgraphy the filter is replaced by long distance microscope. If other sizes should be observed, a suitable lens and camera system may be selected. The working distance for the detection system depends on the lens that is used for imaging. With the QM1 lens (recommended for particle sizes ranging from 5 µm to 500 µm and working distances of more than 50 cm) the minimum distance from the lens to the probe volume is about 0.5 m.

Fig. 0.2 Fuel tank and CCD Camera

2. Nozzle

The nozzle that we use is called swirl nozzle and is provided by Danfoss as shown in fig.3.3. It's have a different mass flow rate start from 1.87 kg/hr. to 7.42 kg/hr. The orifice diameter of nozzle varies from 0.36 to 0.57 mm. It consists of one piece cast body with a removable vane type core. This core features a cylindrical core that functions as plain orifice atomizers to provide drops at the center of the conical spray pattern.

Fig. 0.3 Danfoss nozzle

4. EXPERIMENTAL PROCEDURE

Fuel is filled into a tank and pressurized to the required level (e.g., 4, 6, or 8 bar), with the system designed to withstand pressures up to 14 bar and monitored using a pressure gauge. The pressurized fuel is supplied to a nozzle (5.84 kg/hr or 1.5 GPH) mounted on a traversing system that can move axially and radially. When fuel injection starts, a laser and camera operate simultaneously to capture spray images. These images are processed to determine droplet characteristics such as Sauter Mean Diameter (SMD), breakup length, and velocity. Remaining fuel droplets are collected in a pan. The experiment is repeated at different pressures to find the effective operating pressure, particularly under no co-flow conditions. Image processing is performed using DaVis software. For PIV analysis, "vector processing of double frame" with multi-pass and decreasing interrogation window sizes (45×45 to 90×90) is used for better accuracy. Cross-correlation between interrogation windows in successive frames yields velocity vectors, which can be averaged statistically to obtain mean velocity fields. For shadowgraphy, recorded images are manually assessed and processed in DaVis. The particle report provides histograms and statistics such as SMD, Dv10, Dv50, and Dv90. Additional filtering can be applied based on diameter, centricity, or speed. The primary parameter of interest is the Sauter Mean Diameter (d_{32}), which represents the droplet diameter having the same volume-to-surface-area ratio as the spray and serves as a key indicator of atomization quality. All measurements are carried out using a laser diagnostic system.

4.1 Shadowgraphy setup

Shadowgraphy is an optical backlighting technique used to measure fuel spray parameters by visualizing droplets or bubbles as shown in fig.4.1.It relies on high-resolution imaging with pulsed backlight illumination, where the measurement volume is determined by the focal plane and depth of field of the imaging system. The method is independent of particle shape and material (transparent or opaque) and can measure particle sizes down to about 5 µm with suitable optics and lighting. The light source may be a pulsed laser with dedicated illumination optics or a flash lamp, selected based on particle size and velocity. Very short laser pulses enable motion “freezing” for particles moving at speeds exceeding 100 m/s.

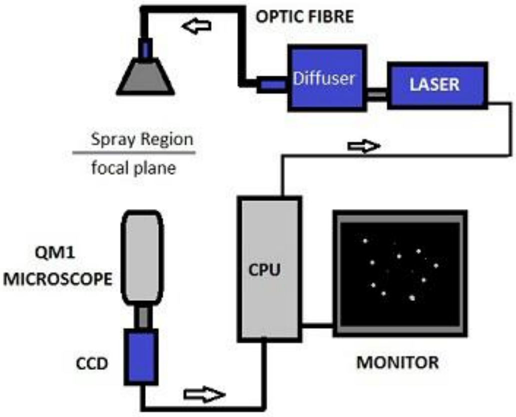


Fig. 4.1 Experimental setup for shadowgraphy

A double-pulse laser combined with a double-frame camera allows investigating size dependent velocities. This technique provides information like size distribution, shape and velocity of particles.

Following are the equipment’s necessary for shadowgraphy.

a. Charge coupled device (CCD) camera.
b. Diffuser.
c. Double cavity laser.
d. Microscope

4.2 Particle Image velocimetry (PIV) setup

Another technique to analyze the parameter is PIV, PIV records the position over time of small tracer particles introduced into the flow to extract the local fluid velocity. Thus, PIV represents a quantitative extension of the qualitative flow visualization techniques that have been practiced for several decades.

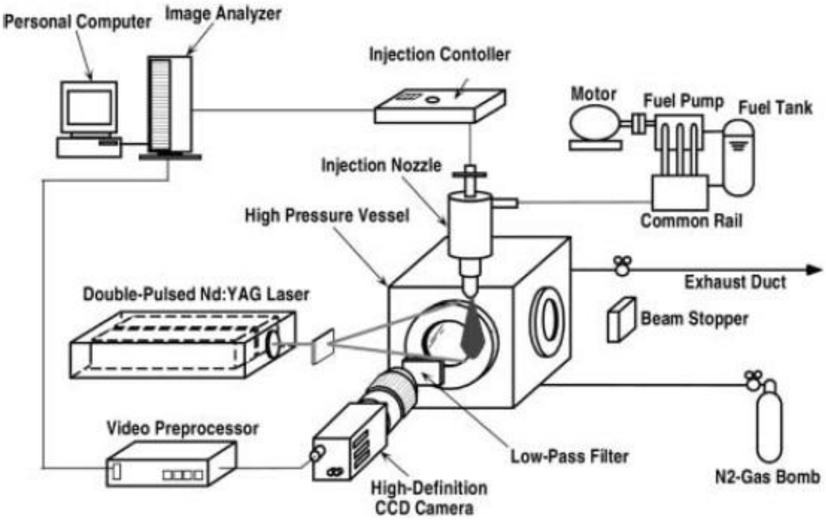


Fig. 4.2 Setup of PIV system

The favored arrangement of a PIV system is that the biggest velocity component of the observed flow field is parallel to the light sheet while the camera viewing direction is normal to the light sheet. Even when the arrangement is restricted by experimental boundary conditions like optical access etc. the setup should not differ too much from the ideal perpendicular arrangement shown in fig 3.12 in order to keep systematic errors as small as possible.

To conduct the experiments, it is necessary to set the nozzle location using traverse system such that the plane of area of interest lies in the window of the camera image and in the plane of laser sheet. Before starting to conduct an experiment, the scaling and calibration has to be done. In order to do this, a simple ruler scale is fitted in the plane of interest and the image of the same is captured without any illumination. Now, the scale is set in Davis software. This has to be done inadvertently or else the system will not calculate the velocity in m/s and the result will be given in pixel/sec, which has no physical meaning. Scaling of PIV is shown in Fig.4.3

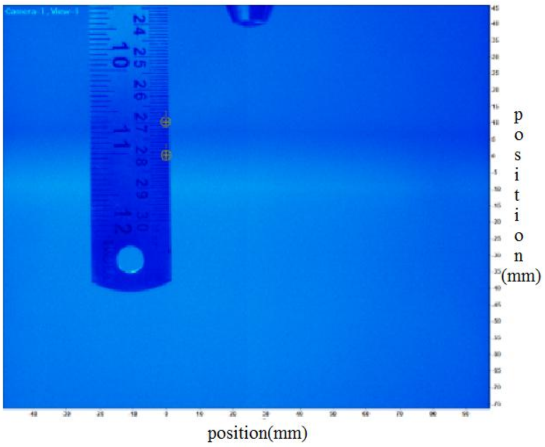


Fig. 4.3 Scaling of PIV

5. RESULT & DISCUSSION

Injection Pressure Effect

There is an effect of injection pressure on the spray parameter the PIV and Shadowgraph experiment was conducted in which pressure swirl nozzle with solid spray cone angle of 45^0 is subjected to injection pressure from 4, 6 and 8 bar with kerosene and diesel as an atomizing liquid. We have taken 200 images of each nozzle and the following result is the mean of that images.

5.1 Velocity and vorticity analysis of kerosene

The following figures 5.1 show the PIV raw image of kerosene spray at 4, 6 and 8 bar pressure which explain the variation in spray with the injection pressure.

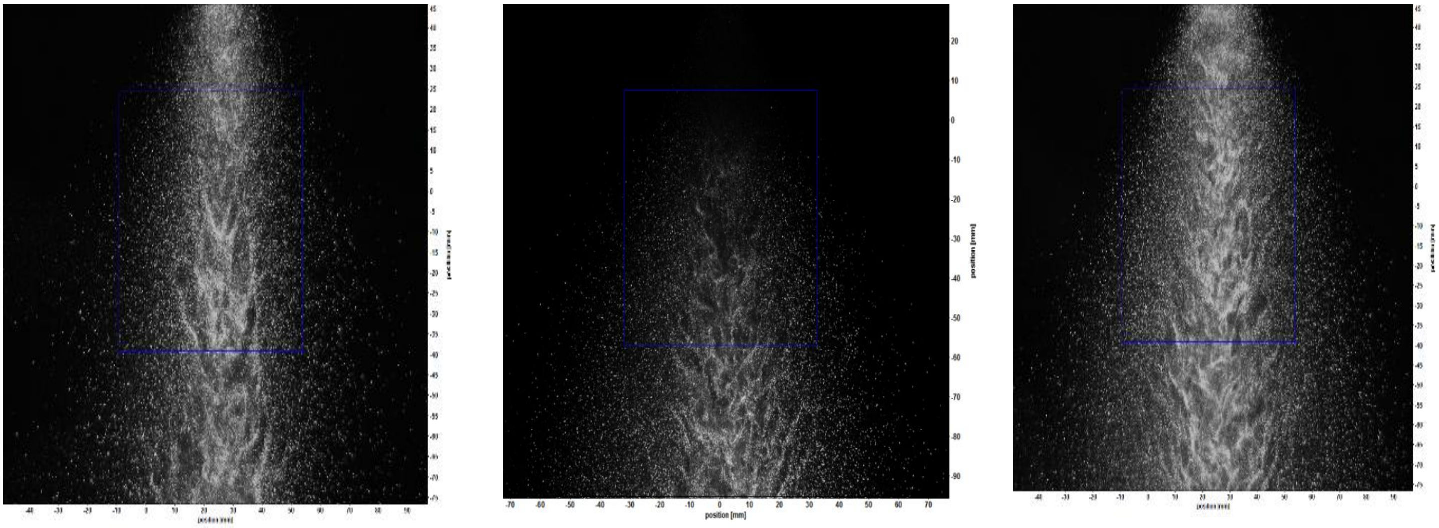


Fig. 0.1 Raw image of kerosene at 4, 6 and 8 bar

The Image explain that the spray cone angle increase from low injection pressure to high injection pressure It can also be observed that most of the liquid mass is near the axis of the spray, this is due to the solid cone spray nozzle design. Hence it can be expected that the result for the hollow cone spray may be opposite.

The size of the window covered by PIV is 120 mm X 100 mm and hence to cover the other part of spray, the nozzle has to be shifted vertically upwards. This ensures that the velocity distribution at various locations is found. In our experiment, we have captured images at locations of 10 mm downstream from nozzle tip but the window size in PIV is large so we can analyze the image at different location. The 10 mm downstream is chosen because in this range of distance the liquid ejecting from the nozzle is still in the form of conical sheet. Also there is one reason to choose this location is when we inject the spray flame in upward direction, the lift of height is calculated as around 10 mm for three nozzle as shown in fig. 5.2

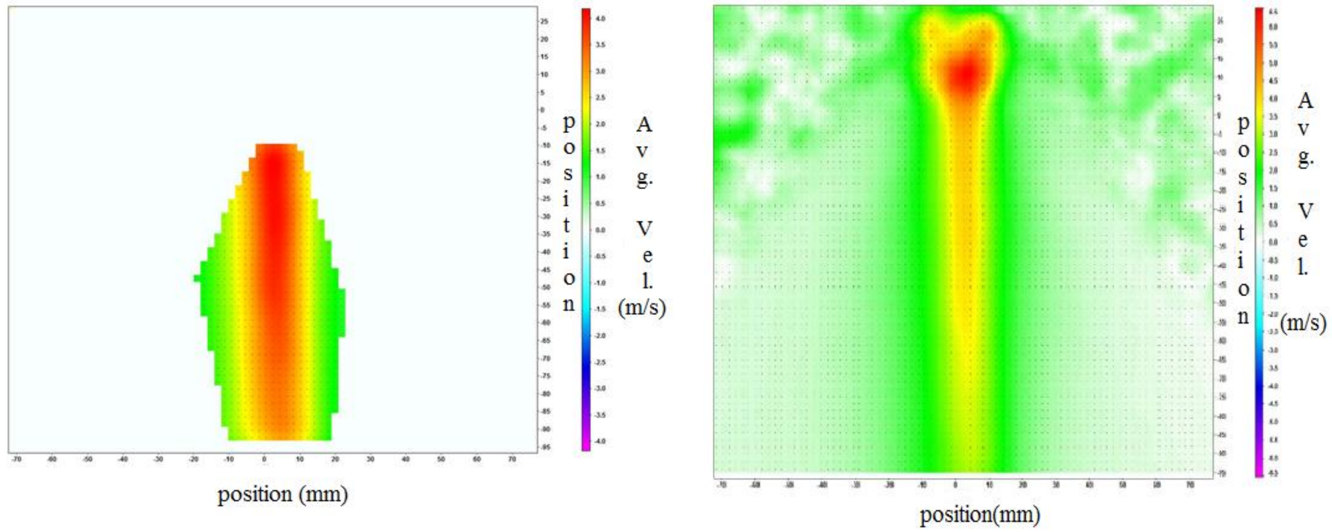


Fig. 0.2 Average velocity variation with position at 5.84 kg/hr. with and without masking at 4 bar.

Table 0.1 Velocity for 5.84 kg/hr. mass flow rate of kerosene

Injection pressure	With masking(m/s)	Without masking(m/s)	Velocity (m/s)
4 bar	3.8	5.8	0.6
6 bar	4.8	6.0	1.2
8 bar	5.4	6.5	1.5

The PIV result of nozzle spray at 10 mm downstream shows that the maximum velocity of the droplet is found near the axis of the spray and the magnitude of the same is found to be 3 to 6 m/s with masking and 5.5 to 6.5 m/s without masking. Also the surrounding air velocity is in the range of 0.6 to 1.5 m/s for mass flow rate of 5.84 kg/hr. as shown in fig.5.5 and the graphical representation is as shown in fig. 5.3 below.

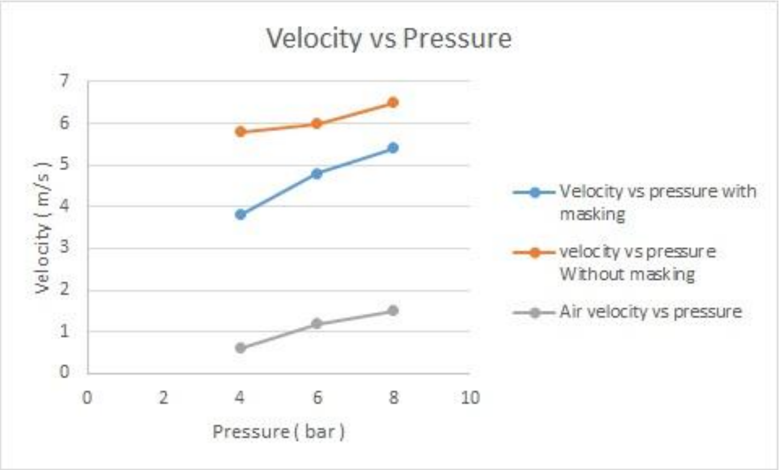


Fig. 0.3 Graphical representation of average velocity variation with position with and without masking at 4, 6 and 8 bar..

5.2 Velocity and Vorticity analysis of Diesel

Similarly for diesel we perform experiments on 4, 6and 8 bar at mass flow rate of 5.84 kg/hr. and 7.42 kg/hr. respectively. In this case also we consider the nozzle distance at 10 mm above the tip after analyzing the spray flame of that nozzle at the above mentioned pressure

In this case the lift of height varies from 15 to 101 mm with vary in mass flow rate. If we compare graph Lift off height v/s mass flow rate for kerosene as well as diesel. We can say that the increase in lift off height in case of diesel is more than that off kerosene. Following fig.5.4 is the results for diesel at mass flow rate of 5.84 kg/hr. and 7.42kg/ hr. at 4 bar injection pressure 20 mm above the nozzle tip with and without masking respectively.

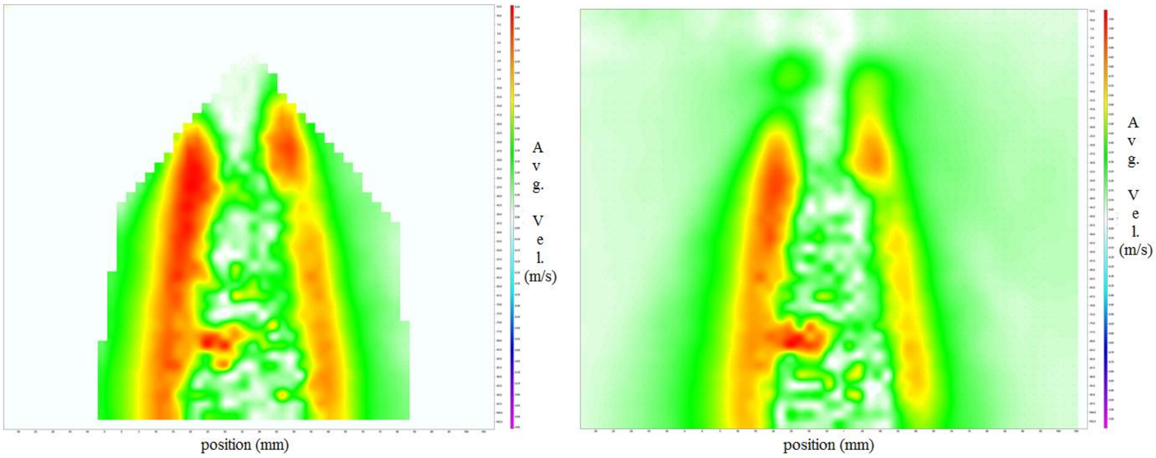


Fig. 0.4 Average velocity variation with position at 5.84 kg/hr. with and without masking at 4 bar

Table 0.2 Velocity for 5.84 kg/hr. mass flow rate of Diesel

Injection Pressure	With masking (m/s)	Without masking (m/s)	Air Velocity (m/s)
4 bar	0.9	0.55	0.1
6 bar	0.98	0.62	0.15
8 bar	1.2	0.85	0.2

In this case, it has been observed that the velocity for 5.84 kg/hr. mass flow rate is varies from 0.9 to 1.2 m/s in case of masking. So as we increased the pressure the velocity slightly increased as compared to kerosene for the same mass flow rate. For without masking the velocity increases from 0.55 to 0.85 m/s as shown in fig 5.10 .The outside air velocity which affects the flow in case of without masking is varies from 0.1 to 0.2 m/s. and the graphical representation for the same is as shown in fig.5.5 below.

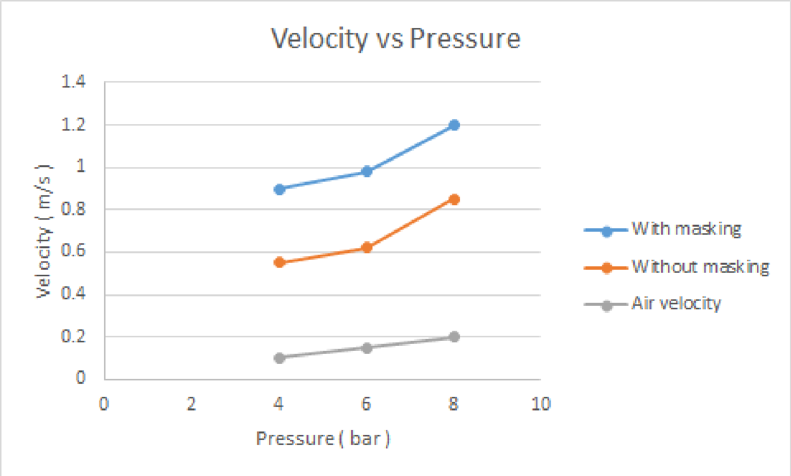


Fig. 0.5 Graphical representation of average velocity variation with position with and without masking at 4, 6 and 8 bar.

5.3 Droplet size measurement

The figure 5.6 shows the raw as well as processed image. Similar images were captured for all three injection pressures and then they were processed for particle sizing in Davis Software. In the processing window the reference file has to be selected first which is the raw image file that was without any spray. Now for particle recognition criteria select the minimum percentage of brightness of the pixel required to be consider as particle. The brightest pixel in the image is considered as 100% bright. The default values given by Davis is 50% brightness as the criteria of recognition but at this value the computer will generate lot of dummy particles of low diameter. Hence the criterion has to be modified to 55 % for accurate recognition and processing.

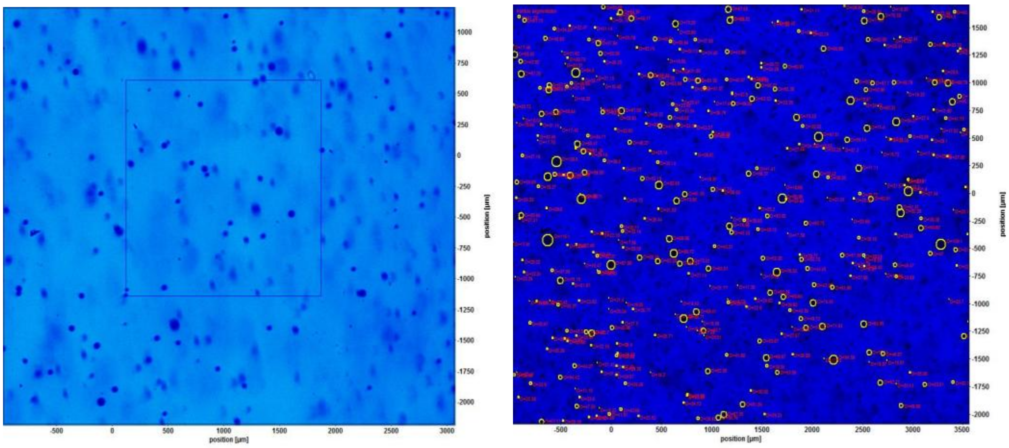
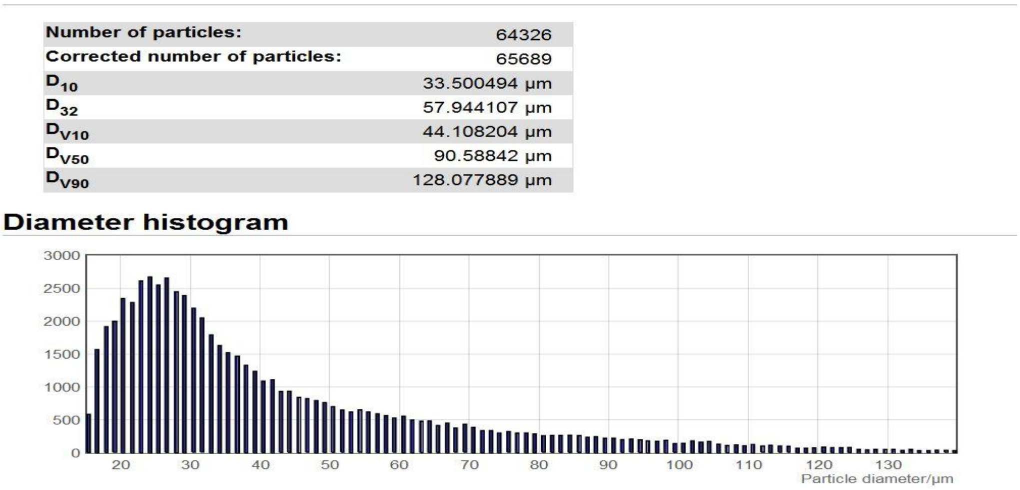


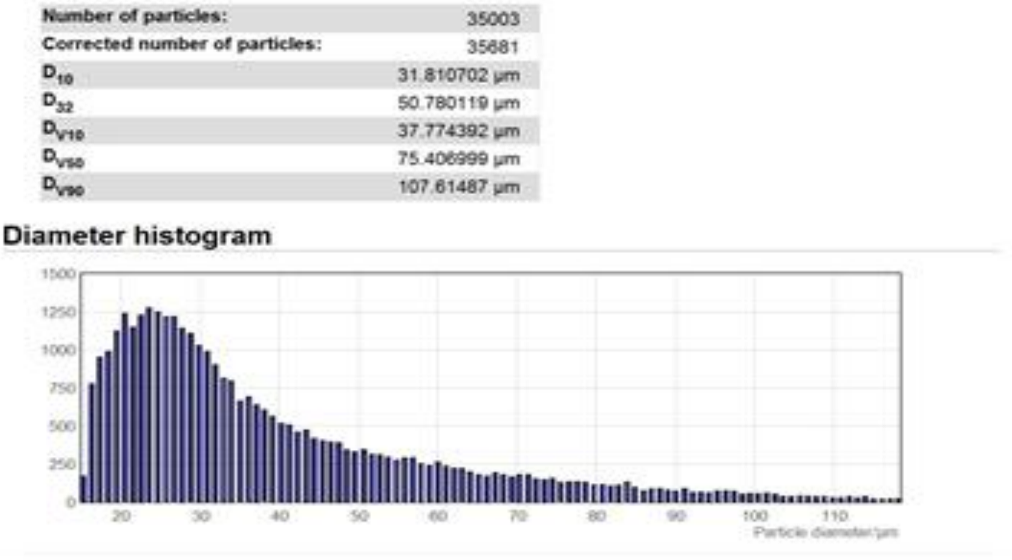
Fig. 0.6 Raw and processed image of particle shadow graph captured at 4 bar

If we analyzed this image carefully then it can be understood that the acceptable size of droplet is in the range of 20 to 80 micron. The other sizes outside this range are not the actual droplets but simply improper particle recognition. The droplet behind the focal plane will look blurred and the computer will consider it as cluster of small particles in the size range of 0 to 20 um, or if the two blurred droplets are very close to each other, then it will consider them as a big single droplet whose size would be in the order of 100 um. So at the time of generating statistical data such as SMD, the particle data has to be the statistics is shown in Fig 5.7



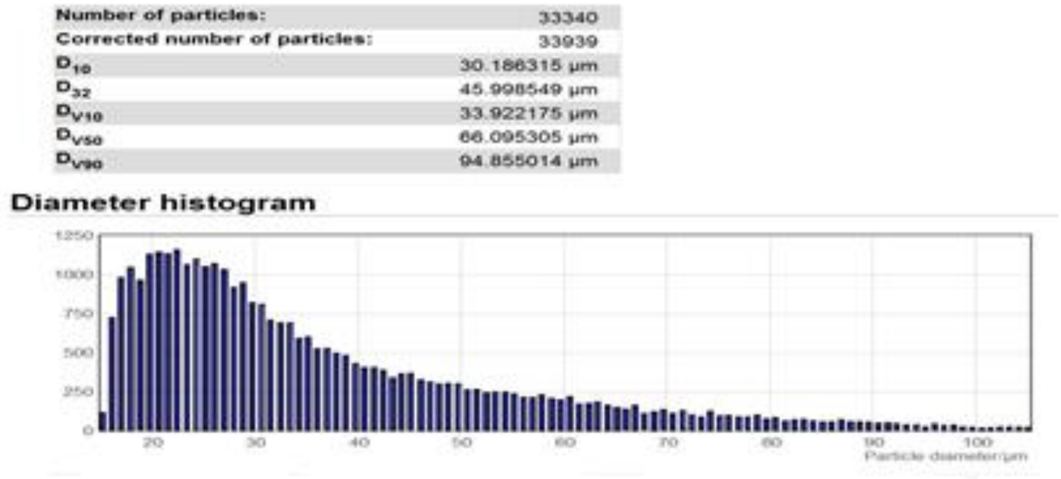
Number of particles:	64326
Corrected number of particles:	65689
D_{10}	33.500494 µm
D_{32}	57.944107 µm
D_{V10}	44.108204 µm
D_{V50}	90.58842 µm
D_{V90}	128.077889 µm

Diameter histogram



Number of particles:	35003
Corrected number of particles:	35681
D_{10}	31.810702 µm
D_{32}	50.780119 µm
D_{V10}	37.774392 µm
D_{V50}	75.406999 µm
D_{V90}	107.61487 µm

Diameter histogram



Number of particles:	33340
Corrected number of particles:	33939
D_{10}	30.186315 µm
D_{32}	45.998549 µm
D_{V10}	33.922175 µm
D_{V50}	66.095305 µm
D_{V90}	94.855014 µm

Diameter histogram

Fig. 0.7 Diameter histogram at 4, 6 and 8 bar injection pressure at 20 mm above the tip of nozzle

6. CONCLUSIONS

PIV results indicate that droplet velocity increases with injection pressure at the same mass flow rate. For kerosene, velocities range from about 3–6 m/s without masking and 5–7 m/s with masking, showing a greater number of high-velocity droplets at mass flow rates of 5.84 kg/hr and 3.72 kg/hr. The surrounding air velocity influencing the flow is about 0.1–1.5 m/s. For diesel, droplet velocities with masking range from 0.9–1.2 m/s at 5.84 and 7.42 kg/hr, while without masking they range from 0.5–1.15 m/s, with air velocity around 0.1–0.4 m/s. Increased vorticity is observed as the spray moves downward.

Shadowgraphy results show that kerosene droplet size decreases significantly as injection pressure increases from 4 to 8 bar, indicating finer atomization by the pressure swirl nozzle without major changes in velocity distribution. The SMD of kerosene spray lies between 35–58 µm. In non-reacting sprays, SMD initially decreases with axial distance from the nozzle and then increases at a mass flow rate of 7.42 kg/hr and pressures of 4–8 bar. Droplet centricity ranges from 0.7–0.9, close to unity, indicating good atomization quality.

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