Characterization of Multiphase Spray using Laser Diagnostics

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

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DEC 2019

CANDIDATE’S DECLARATION

I hereby declare that the project entitled **“Characterization of Multiphase Spray using Laser Diagnostics”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in ‘Mechanical Engineering’ completed under the supervision of **Dr. Devendra Deshmukh, Associate Professor, Dept. of Mechanical Engineering,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

SHUBHANKAR NATH

CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Dr. DEVENDRA DESHMUKH
Associate Professor

Preface

This report on “Characterization of Multiphase Spray using Laser Diagnostics" is prepared under the guidance of Dr. Devendra Deshmukh and Dr. Yogeshwar Nath Mishra.

In this report, it is demonstrated that the highly dense diesel spray is analyzed with the help of PDIA and PLIF imaging techniques. PDIA provided us the Liquid Volume Fraction of a small regime of the transient spray with high accuracy. PLIF imaging technique is a versatile method of imaging spray. In PLIF, a thin laser sheet was passed through the spray and after interaction of laser sheet with spray droplets, the droplets emitted fluorescence. CCD camera recorded the gradient in fluorescence intensity along the spray. Here in this report, a detailed description of optical setup and other design parameters are illustrated.

The multiple scattering and optical losses are indispensable part of the system. It is reduced by combining PLIF imaging technique with SLIPI technique. The combined result of SLIPI with PLIF were impervious to optical losses. The accuracy of the results significantly improved. The techniques utilized were economically feasible and less complicated. The images and 3-D models are also attached to make it more illustrative. Here, we have also demonstrated the optimum use of dye concentration and optimum selection of spatial frequency of Ronchi grating for reliable SLIPI images.

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Acknowledgements

I wish to thank Dr. Devendra Deshmukh and Dr. Yogeshwar Nath Mishra for their kind support and valuable guidance.

I would like to thank, Deshmukh Sir for his limitless support. He has given me a wide range of exposure from spray to engines. His friendly nature has made me comfortable to share my views and opinions with him. He was always available for discussions and doubt-solving. Because of Deshmukh Sir, I had the opportunity to meet with Yogeshwar Sir. I am glad that, I had an opportunity to have a supervisor like Deshmukh Sir and I will always be grateful to him for his support.

I would like to thank, Yogeshwar Sir for his vast experience and knowledge accompanied with myriad of ideas to tackle a difficult task. Sir, you are an inspiration on how to become a perfectionist in research. Your amiable and cheerful nature, led to better understanding of the concepts and results. I am glad that I had an opportunity to learn from you.

The Maheshwar trip with Deshmukh Sir and Yogeshwar Sir will always be a memorable and mesmerizing excursion for me.

I am thankful and grateful to my parents for their support and endless love. [मै हमेशा उनका ऋणी रहूँगा]. My mother, Rupa Nath is the source of all the moral values and behaviors, I inculcate and from my father, Kishor Nath I learnt how to do hard work persistently. They are the reason behind my each and every achievement. Their effort and love to shape my future and provide me everything that I needed is treasure of my life. They are the backbone of my life. I am thankful to god to make me your child.

It is their help and support, due to which I became able to complete the experiment and technical report.

I would like to thanks PhD TA Vishal sir for helping me with the experiments and Vasudev sir for assisting me, and Devashish sir for teaching me managerial skills. I will miss the long discussions we used to do to come up with proper parameters to do experiments and futile hammering on the engine and its accessories. They were always cheerful and always found a way out of the anxiety.

Without their support this report would not have been possible.

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Abstract

A multiphase spray is characterized using laser-based techniques in the current project. Emphasis is given to measurement of liquid volume fraction (LVF) of spray using PLANAR LASER INDUCED FLUORESCENCE (PLIF) and PARTICLE/DROPLET IMAGE ANALYSIS (PDIA) technique. Computation of LVF at any location helps to estimate the amount of liquid present at that location. Qualitatively, low LVF regions have high evaporation rate and lower air-fuel ratio in combustion environment. Structured Laser Illumination Planar Imaging (SLIPI) technique has been employed to study LVF of spray, owing to the non-intrusiveness of the method. Since, intrusive methods have a major drawback of inducing perturbation in the flow field and provides erroneous results. The SLIPI method is employed to reduce the effect of multiple scattering in multiphase flows.

Thin planar spatially modulated laser sheet (SLIPI) is passed through the diesel spray and the fluorescence emitted by the spray is captured by CCD camera kept at right angle to direction of propagation of laser sheet. The diesel spray is injected at room temperature with 500 bar pressure. Image resolution and fluorescence signal is enhanced by mixing of Rhodamine dye in the fuel. Till now, we have completed acquisition of images of diesel spray. PDIA technique will be equipped to calibrate these intensity gradients. In this method, microscopic imaging is performed in specified regions of the spray to measure droplet diameters. These diameters are utilized to calculate LVF at that location. Utilizing PDIA, calibration constant is generated by correlating LVF with the intensity at the same location recorded by the SLIPI method. In conclusion, Liquid volume fraction distribution and evaporation rate will be inferred from the results.

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Nomenclature

CCD	Charge-Coupled Device
CO	Carbon monoxide
Conv. LSD	Conventional LSD measurements
DOF	Depth-of-Field
FWHM	Full Width at Half Maximum
ILIDS	Interferometric Laser Imaging for Droplet Sizing
LDM	Long Distance Microscope
LIEF	Laser Induced Exciplex Fluorescence
lp/inch	Line pairs per inch
LSD	Laser Sheet Drop sizing
MDR	Morphology-Dependent Resonances
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
NOx	Nitrogen Oxides
OD	Optical Depth
PDA	Phase Doppler Anemometry
PDI	Phase Doppler Interferometry
PDIA	Particle/Droplet Imaging Analysis
PDPA	Phase Doppler Particle Analyzer
PLIF	Planar Laser Induced Fluorescence
SLIPI	Structured Laser Illumination Planar Imaging

Chapter 1
INTRODUCTION

Today, the increased concerns towards mitigation of emissions have paved a new path towards development of new equipment and techniques to analyze spray and its characteristics. Due to surfeit advancement in the field of lasers and imaging technology, non-intrusive optical methods have been developed yielding high accuracy and reliability. Spray characteristics such as tip penetration length, cone angle, liquid volume fraction, droplet size and temperature are scrutinized using optical methods. Optical techniques namely PDIA (Particle/droplet image analysis), LSD (Laser sheet drop-sizing), LIF/Mie ratio, Rainbow refractometry, Raman Scattering, Laser induced fluorescence (LIF) and many other techniques are utilized depending on their applications. Limitations are indispensable to any machine or system. The same is true for these optical methods. Multiple scattering, indirect reflections and background light induces vulnerability to error and reduces accuracy. SLIPI (Structured laser illumination planar imaging) is developed to circumvent this issue. In a recent article [1], Mishra et al. have demonstrated that removing the contribution of multiply scattered light using SLIPI significantly improve the measurement accuracy when assessing the droplet Sauter Mean Diameter (SMD) through the ratio of LIF/Mie-scattering.

LVF measurement of fluids is of great importance for various industrial applications. Computation of liquid volume fraction (LVF) at any location helps to estimate the amount of liquid present at that location. Qualitatively, low LVF regions have high evaporation rate and lower air/fuel mixture in the system. Evaluation of the distribution of LVF assists in optimizing the system design. For example, in spray systems the ability to control droplet evaporation, dependent on liquid volume fraction is highly desired, especially in liquid fuel combustion devices as well as for spray cooling/drying applications. In internal combustion engines, droplets are required to evaporate on the order of milliseconds in order to form the adequate fuel/air mixture proportion prior to ignition. Optical methods such as PDIA, LSD, PDA, LIF/Mie ratio along with LIF have been applied to estimate LVF in sprays.

PDIA in combination with LIF deduces LVF of spray [2]. PDIA technique relies on point scanning and hence it is time consuming. PDIA provides us LVF at any point in the spray. The PDIA technique gives droplet diameter and shape information and has been validated with PDPA measurements [6]. LIF is directly proportional to the liquid volume [14].

Combining LVF and PDIA, distribution of LVF along the spray is estimated. Also, laser beam scattering and extinction utilizing infrared wavelength was used by Labs and Parker [7] to obtain liquid volume fraction and Sauter Mean Diameter (SMD) data in diesel sprays at high gas pressures under evaporating and non-evaporating conditions.

LIF/Mie ratio provides us the Sauter mean diameter (SMD) of droplets in a spray regime. This measurement technique is based on laser sheet illumination and provides spatially resolved maps of LVF. In order to apply it, simultaneous LIF and Mie images are recorded and their ratio is calculated which is proportional to SMD and then it is calibrated utilizing PDA. Similarly, number density is calculated using extinction coefficient. Then SMD in association with number density of droplets deduces LVF [3].

In this report, we address the issues associated with multiple light scattering in LVF measurements of highly dense diesel spray, by combining SLIPI with PDIA. The effect of dye concentration and grating frequency are also investigated. In our experiment, we examined diesel fuel at an injection pressure of 500 bar, with pyrromethene dye dissolved in it.

A novel methodology is proposed to estimate planar liquid volume fraction distribution of highly dense diesel spray using SLIPI-PLIF and PDIA. Due to mitigation of optical losses and multiple scattering, the results are reliable and accurate

Chapter 2
LITERATURE REVIEW

Atomization governs process efficiency in many industrial applications such as spray coating, pharmaceutical applications, combustion devices [15]. Air-fuel mixture formation process, and hence combustion and emission, is controlled by the drop-size and liquid fuel distribution in a combustor [16,18,19]. Therefore, a reliable measurement of drop sizes and the distribution of liquid fuel (liquid volume fraction) is necessary for optimizing air-fuel mixture formation in a combustion process.

In this chapter, a brief review of laser-based drop-sizing techniques is presented followed by a detailed discussion on LSD technique. The following sections present a summary of principles, assumptions and recent advancements in the LSD technique. Further, different sources of error and methods to compensate these errors are discussed in detail. A brief discussion on various drop sizing techniques is also provided.

Several state-of-the-art laser-based drop-sizing techniques are available: Few of them are listed below:

- Laser-diffraction based drop size measurements.
- Particle/Droplet Imaging Analysis (PDIA).
- Phase Doppler Interferometry (PDI).
- Laser Sheet Drop sizing (LSD)

Laser-diffraction based drop size measurements:

This is a commonly used technique and is also known as Malvern particle sizer. The technique is based on Fraunhofer diffraction of a monochromatic laser beam [20]. Line of sight drop-size measurements are obtained using forward scattering. Thus, spatial variations along the line-of-sight cannot be determined. The technique also suffers from laser beam extinction and multiple scattering [21]. These limitations lead to erroneous drop size measurements in dense sprays [20-22].

Particle/Droplet Imaging Analysis (PDIA):

PDIA is a microscopic shadowgraphy-based direct imaging technique applied in many spray systems including dense sprays [6,23,24]. In this technique, microscopic shadowgraphs are captured using a high-resolution CCD camera coupled to a microscope [11, 25]. A long-distance microscope is used to probe into a very small field of view (~2 mm X 3 mm) with a pixel resolution of the order of a few microns per pixel. The microscopic images are analyzed using image processing tools to obtain statistically large number of droplets and mean drop size. The technique has a capability to consider non-spherical droplets and a presence of a number of droplets in a measurement volume [26, 27]. However, the technique is biased towards large size droplets as the resolution of the technique is diffraction-limited, and small droplets are neglected in the drop-sizing [26, 29].

Phase Doppler Interferometry (PDI):

PDI is an interferometry-based drop-sizing technique that uses Mie scattering theory to calculate drop size along with velocity at a point in a spray [20]. PDI is also known as Phase Doppler Anemometry (PDA) or Phase Doppler Particle Analyzer (PDPA). PDI is a widely accepted standard method in the spray diagnostics. However, single droplet occupancy, spherical droplets and multiple scattering are some of the limitations of the PDI technique [20, 22, 28]. Therefore, drop-sizing with PDI becomes questionable when spray is optically thick (optical density>10) such as in non-evaporative, high-pressure diesel sprays. State of art of PDI technique for drop size measurement is well-documented in the literature [22, 30].

Interferometric Laser Imaging for Droplet Sizing (ILIDS)

Another technique in drop sizing is Interferometric Laser Imaging for Droplet Sizing (ILIDS). This technique is also known as IPI (Interferometric Particle Imaging) or PPIA (Planar Particle Image Analysis). Glare points are formed due to interference of reflection and refraction on the droplet surface. The glare points are imaged out-of-focus to calculate drop size. In this technique, micron-ranged droplets can be imaged in a relatively large field of view. However, interference fringes are overlapped when droplet number density is high. Therefore, this technique is limited in sparse sprays where droplet number density is low. A comprehensive review of ILIDS technique can be found in the literature

Laser Sheet Drop sizing (LSD):

Laser Sheet Drop sizing (LSD, also called as Planar Drop Sizing, LIF/Mie ratio technique) is a combination of PLIF (Planar Laser Induced Fluorescence) and Mie scattering imaging that gives a distribution of SMD in a plane of the spray [31- 36]. The PLIF signal is proportional to the volume of the droplet whereas, the scattering signal is proportional to surface area of the droplet [31–34]. The ratio of these two signals is then proportional to SMD. Initially, the basic principle was explained and applied to non-evaporative diesel sprays [30]. The accuracy of the technique has been verified with established drop sizing methods such as PDPA [34, 36] and diffraction-based drop sizing [21]. Overall, the LSD technique is well-established in the spray diagnostics. Table 2.1 lists various laser-based drop-sizing techniques along with the measurement principle of the technique. Further, a major limitation of the technique is also given in the table. Except LSD, these techniques are either point measurement techniques (PDIA or PDI or ILIDS) or line-of-sight (diffraction-based techniques) and, involve long measurement time to get spatial distribution of droplet size in a spray. These techniques also have limitation in sprays with high droplet number density. Large number of droplets in a small volume affect travel of laser light and signal through spray. The LSD technique is an attractive drop-sizing technique that provides SMD and liquid volume fraction distribution in a plane. Moreover, the technique can also be used in dense sprays where droplet number density is high. In the following sections, a detailed description on LSD measurements is provided on principles, assumptions and limitations. It also discusses approaches used, various sources of error and methods to overcome these errors in the LSD technique.

Objectives of the thesis:

The objective of the thesis is to study highly dense diesel spray characteristics and to develop a method to quantify liquid volume fraction of diesel spray. The objectives are:

- To study diesel spray characteristics using laser based optical techniques.
- To reduce loss in Mie and PLIF signals due to multiple scattering, absorption and scattering of the laser sheet and auto-absorption of the PLIF signal using experimental and numerical methods.
- To measure Planar Liquid Volume Fraction using SLIPI-LSD technique combined with PDIA.
- To obtain a correlation between temperature and Liquid Volume Fraction.

Chapter 3
DESCRIPTION OF IMAGING TECHNIQUES

3.1 SLIPI

SLIPI is a technique inspired from structured illumination microscopy [8] and was developed in order to imaging optically dense spray where the majority of photons leaving the medium have undergone multiple scattering events [9, 10]. A Ronchi grating is usually used to imprint a modulated pattern along the vertical direction of the light sheet. The frequency of the grating influences the SLIPI lines pattern. The finer the grating frequency finer is the resulting lines pattern. This special characteristic of SLIPI serve as a signature to tag the singly scattered photons from the illuminated plane. These singly scattered photons 'remember' the modulated signature, but the multiply scattered photons will 'forget' it rapidly while crossing a scattering medium like a spray system. Thus, the undisturbed modulated component, becomes a faithful representation of single light scattering.

SLIPI have 3 categories namely: 1) 1phase(1p); 2) 2phase and 3) 3phase(3p).

A 1p-SLIPI system provides images with less clarity as it rejects all high spatial frequencies above the frequency of the incident illumination. Depending on the applied modulation frequency, certain fine structural spray may be unresolvable with a 1p-SLIPI setup. The optical arrangement of 1p-SLIPI is significantly less complicated and cost effective compared to 2p-SLIPI.

The 2p-SLIPI preserves nearly the full spatial resolution offered by the imaging system, rejecting only some specific high spatial frequencies (those coinciding with residual structures). In terms of optical arrangement, the 2p-SLIPI approach is more complex, since it requires the use of two pulsed laser systems and a detector capable of recording the two sub-images on a sub-microsecond time scale to capture the transient spray. In addition, the phase between the two sub-images should be precisely equal to half of modulation period. Here, in this report, we have utilized 1p SLIPI due to ease of operation and low capital cost but the images are deduced at the cost of image resolution.

The 3p-SLIPI approach consists in recording a minimum of three sub-images to construct of the final demodulated image. The line pattern, which is encoding the light sheet, is preserved by the photons that have experienced a single scattering event, while, on the contrary, photons that have undergone several scattering events will lose this structural information, i.e., contribute to a non-modulated intensity component in the detected image. Deducing the light intensity from the singly scattered light consists, then, in measuring the amplitude of the coded modulation. If a sinusoidal pattern is superimposed upon the light sheet, then the resulting image intensity $I\,(x, y)$ is described as:

$$I\,(x, y) = I_c(x, y) + I_s(x, y).\ \sin\,(2\pi x v + \phi), \qquad 1$$

where v represents the spatial frequency of the modulation and ϕ is the spatial phase.

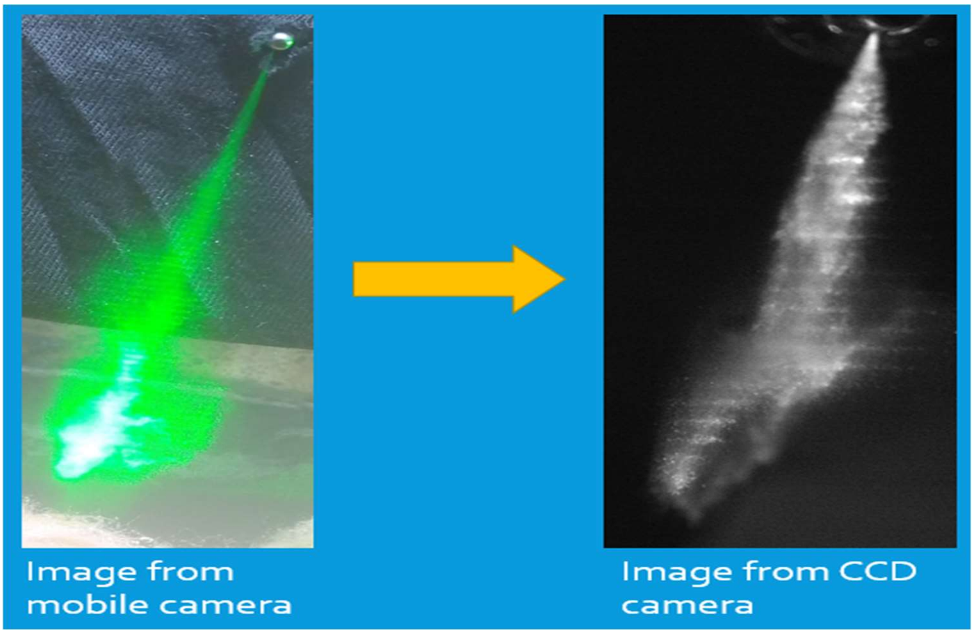

Figure 1: Example of line patterns superimposed on spray.

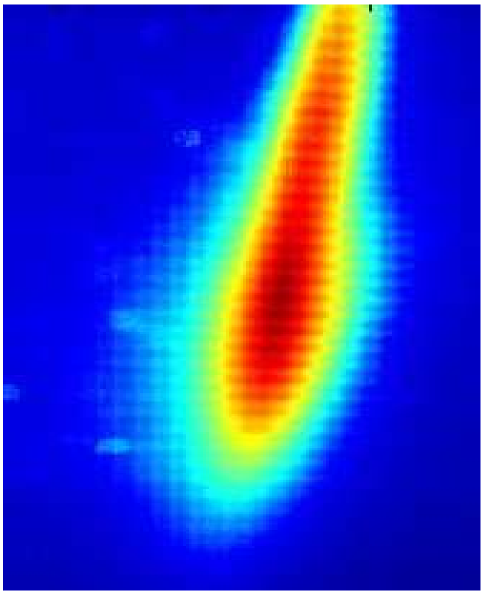

Figure 2: SLIPI image of diesel spray at 1ms injection duration

Here, $I_C(x,y)$ is the intensity corresponding to singly and multiply scattered photons (conventional) and $I_S(x,y)$ represents the amplitude of the modulation from the singly scattered photons (SLIPI) only. To extract the information corresponding to I_S (x, y) in Eq. (1), three sub-images I_0, I_{120}, and I_{240} need to be recorded, having the respective spatial phases of 0°, 12°, and 240°. Using these sub-images, an SLIPI image can be constructed from the root mean square of the differences between sub-image pairs, described mathematically as:

$$I_S = (\sqrt{2})/3[(I_0-I_{120})^2+(I_0-I_{240})^2+(I_{120}-I_{240})^2]^{1/2}.$$

Although, despite the ability of obtaining 'instantaneous' images in the near-field spray region with no image blur, the hardware cost and complexity of such a 3p-SLIPI clearly limit its applicability in practice.

3.2 PDIA (Particle/Droplet Image analysis)

The PDIA technique can be used in dense diesel sprays [6]. The PDIA technique gives droplet diameter and shape information and has been validated with PDPA measurements [11]. PDIA is a reliable, repeatable and robust technique for the sizing of spherical and non-spherical droplets. The accuracy of the PDIA imaging system for small spherical objects is dependent upon three main factors, the effects of diffraction, defocus and optical resolution (i.e. number of pixels per micron). The novelty of PDIA lies in the automated image postprocessing routine which uses a segmentation thresholding algorithm for the quantitative analysis of droplet or particle images.

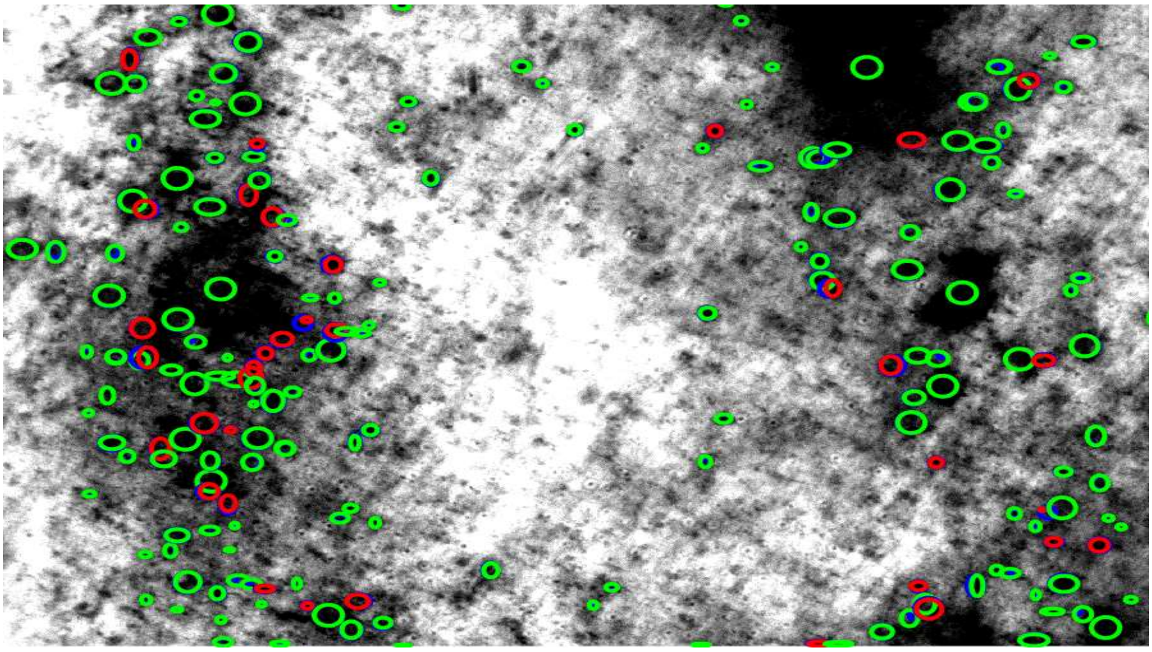

Figure 3: Image processing based on 'Threshold algorithm' for droplet acquisition

In PDIA, images of small region of spray with uniform background intensity is recorded. Diffused back-illumination is utilized to avoid non-uniform lighting of sprays and reduce the effects of beam-steering on the images. In PDIA, the image consists of focused and defocused droplets which are quantified with the help of depth of field (DOF) calibration. These calibrations provide the value for low threshold and high threshold values. Then PDIA technique uses an automated segmented thresholding algorithm for the quantitative analysis of droplet or particle images. A binary image is obtained from a microscopic image using a global threshold. Then an image segmentation algorithm is used along with high and low threshold values to identify the center of a droplet, an effective area of the droplet and other droplet parameters.

Chapter 4
EXPERIMENTAL SET-UP

4.1 SLIPI PLIF set-up

The 1p-SLIPI optical setup for imaging of the liquid LIF is shown in figure 4. One sub-images for each detection is acquired by using scientific 14-bit CCD camera (PCO SENSICAM) with F-32 sigma macro objective lens for high spatial resolution. Each acquired image is represented by 1200×1600 pixels with exposure of 1µs. For the illumination of spray pulsed 532nm Nd:YAG laser (type: Bernoulli PIV) were employed. The pulse duration is in the order of 10ns, while the pulse repetition rate is 1 Hz. Collimation of laser light was prepared using 1negative spherical lens (f = -25mm) and 1positive spherical lens (f = 150mm). The resulted collimated beam is superimposed through a Ronchi grating with 100 line-pairs/inch spatial frequency to create the line pattern on the laser beam. Now spatially modulated light sheet is formed by passing the beam through 2positive cylindrical lenses (f =1000mm and f =150mm). As the fluorescent tracer, a diesel soluble dye Pyrromethene 597-C8 is maintained in the diesel fuel at a concentration of 8mg/L. The LIF emission is detected by using a 532 nm (12 nm FWHM) notch filter just in front of CCD chip in order to exclude the excitation light.

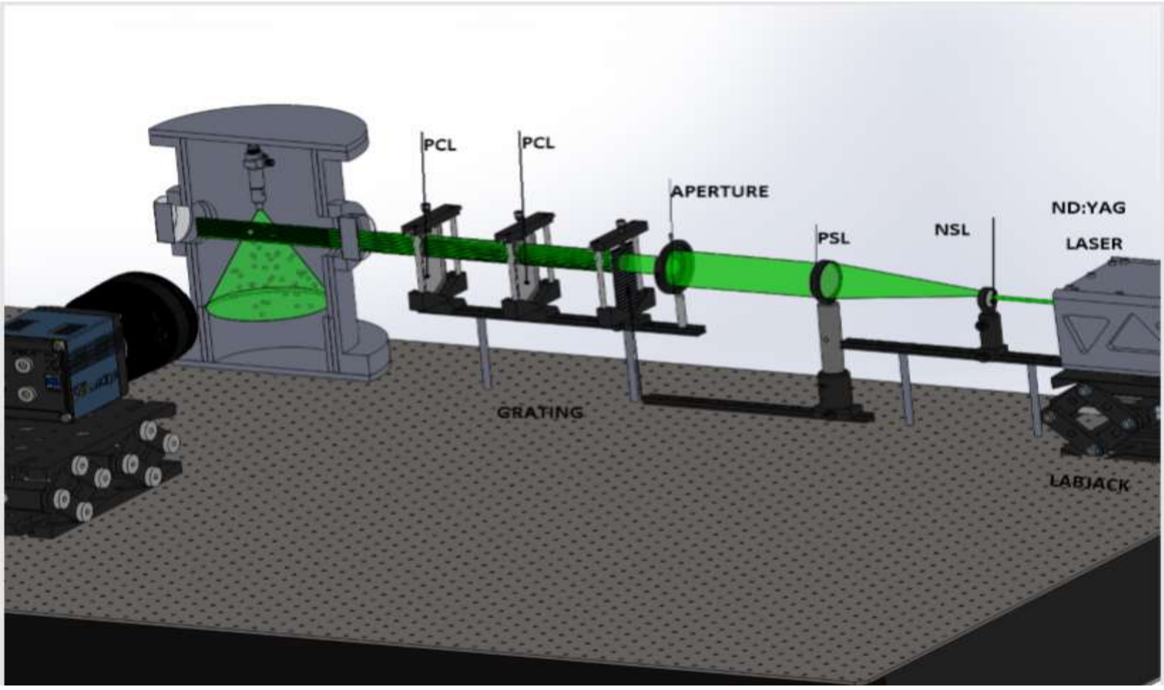

Figure 4: Optical setup of SLIPI LIF

The PLIF experiments are performed using a low dye concentration and laser power to obtain reliable PLIF signals. The experiments are conducted in a linear regime of proportionality between fluorescence signal and incident laser energy. The linearity of the PLIF signal with incident laser power and dye concentration is confirmed using a cuvette experiment. The standard cuvette experiments are performed with a cuvette cell filled with a liquid of various dye concentrations. The PLIF signal is observed to be a linear function of the concentration of Pyrromethene dye. Further, the validity of the PLIF measurements in the linear regime is confirmed by varying the incident laser energy with a dye concentration of 8 mg/L in the cuvette. The experiments are conducted with 8 mg/L concentration which follows the linear regime.

A Ronchi grating generates harmonics of the fundamental frequency due to diffraction of the laser light which may lead to unwanted residual line structures in the final SLIPI image. These higher order harmonics are restricted to enter into the field of view using a frequency cutter. Approximately 300 images are averaged to remove any temporal fluctuations in the spray images.

The line patterns made from Ronchi grating of spatial frequency 10lp/mm is superimposed on a cuvette filled with solution of Rhodamine-6G. The fine line patterns are clearly visible in the figure 5. Same modulated laser sheet is superimposed on the diesel spray, but due to its highly dense nature and high multiple scattering the line patterns are completely destroyed and are not visible in the spray as well as in the FFT image as shown in figure 6.

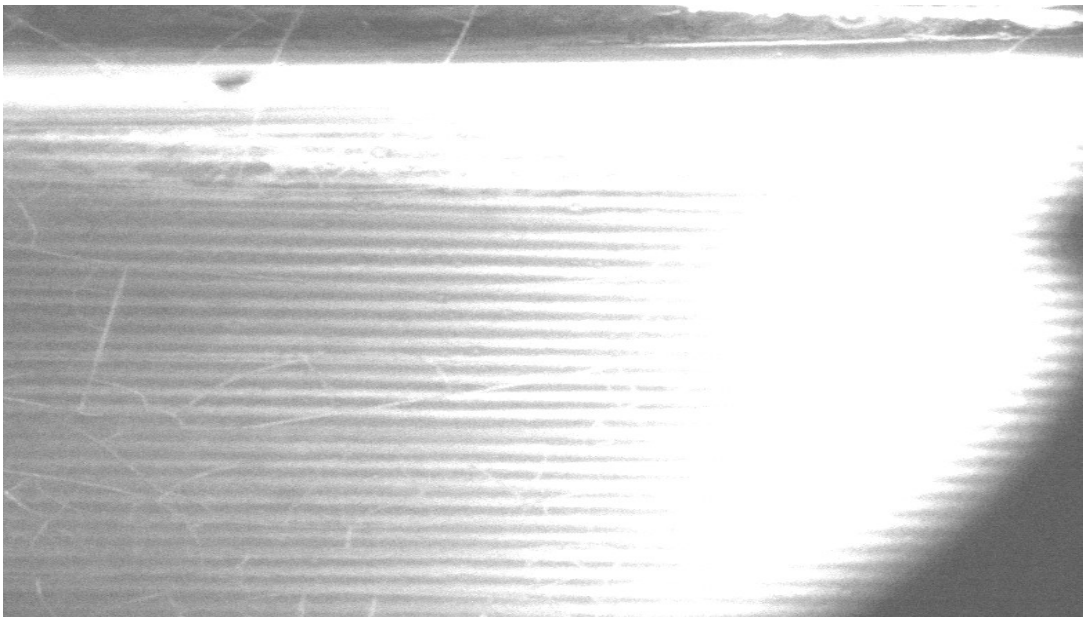

Figure 5: Line patterns of 10 lp/mm Ronchi grating superimposed on cuvette.

The diesel spray is investigated at room temperature and atmospheric pressure condition using CRDI system and solenoid injector. The injection pressure is fixed at 550 bar and injection duration of 1ms. The spray is illuminated 300μs after SOI (start of injection) with modulated laser sheet of 5cm in height and thickness of 1mm.

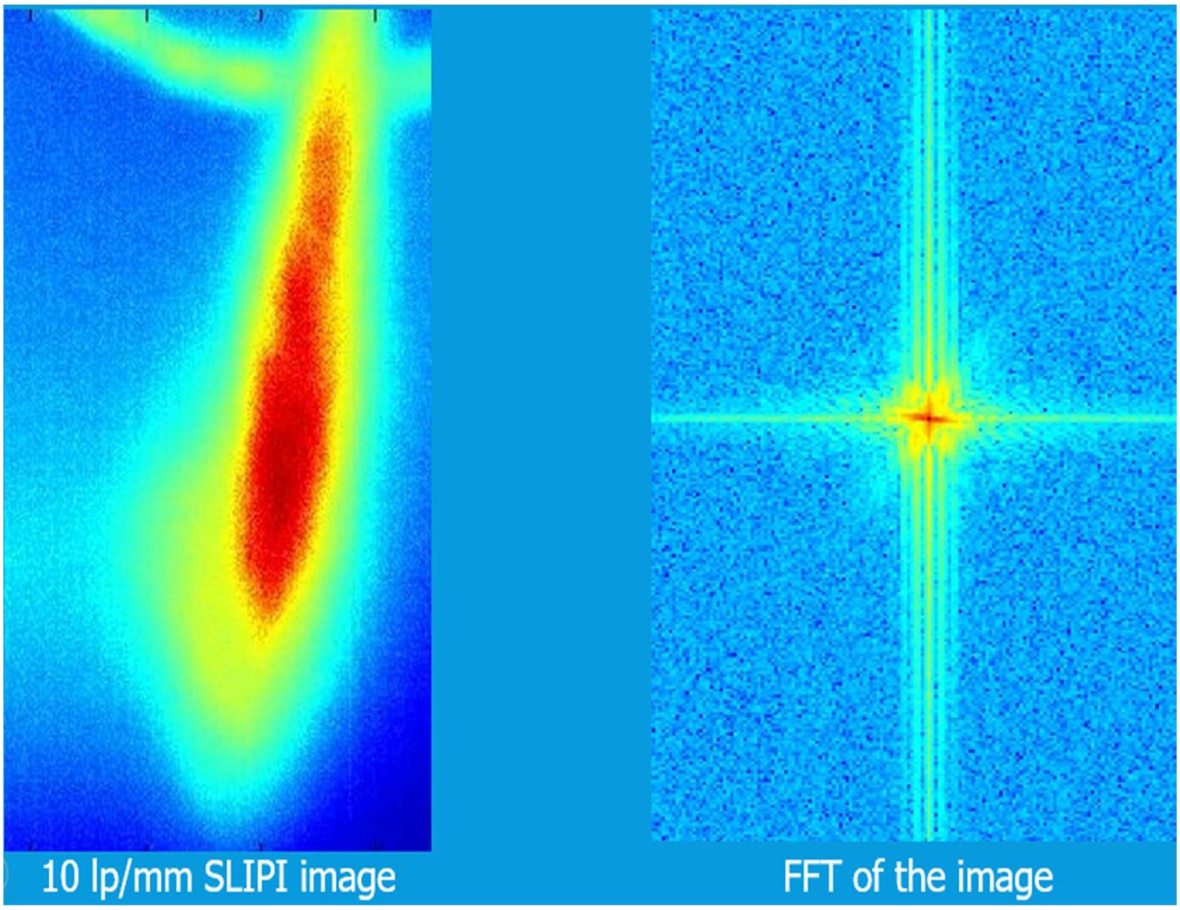

Figure 6: SLIPI and FFT image of spray superimposed with 10lp/mm.

4.2 PDIA setup

The experimental setup for the PDIA technique consists of a long-distance microscope coupled with a CCD camera to obtain a field of view of 2.1mm × 3.3 mm. The dept of field of the optical setup was calculated using Patterson globe. PDIA measurements were obtained using a pulsed laser (Litron Lasers, Bernoulli PIV) of 532 nm as an illumination source with a pulse duration of 10 ns, maximum pulse energy of 200 mJ and a camera exposure time of 1µs. The depth of field (DOF) of the optical system is measured using a Patterson Globe (Pyser, NG1 Patterson globes and circles). The Patterson Globe has circles with diameter from 18 µm to 450 µm. The Patterson Globe is moved in a step of 50 µm from either side of the focal plane to determine DOF correction factor for various diameters. The resolution of the PDIA technique is limited by the diffraction limit of the optical system and a minimum number of pixels per droplet [37, 38]. The minimum droplet diameter detectable with the PDIA system in the present work is kept at 7 µm. This avoids diffraction limit and also measures droplets with acceptable accuracy. Droplets with a diameter less than 7 µm are neglected in SMD calculation. To generate an image with a uniform background intensity distribution it was necessary to diffuse the coherent laser light beam and this was achieved through the use of cuvette filled with solution of Rhodamine dye and water, placed in the beam path. Image acquisition was achieved with a 14-bit CCD camera (PCO SENSICAM) with a 1200 ×1600-pixel array. A Long-distance microscope of front lens focal length of 51 mm offering a resolution of 1.875 µm/pixel. Figure 7 shows a typical 'global' spray image at 300 µs after SOI for P_{inj}= 550 bar and a corresponding high magnification image obtained at the measurement location in a relatively dense region of the diesel spray with an injection duration of 1ms.

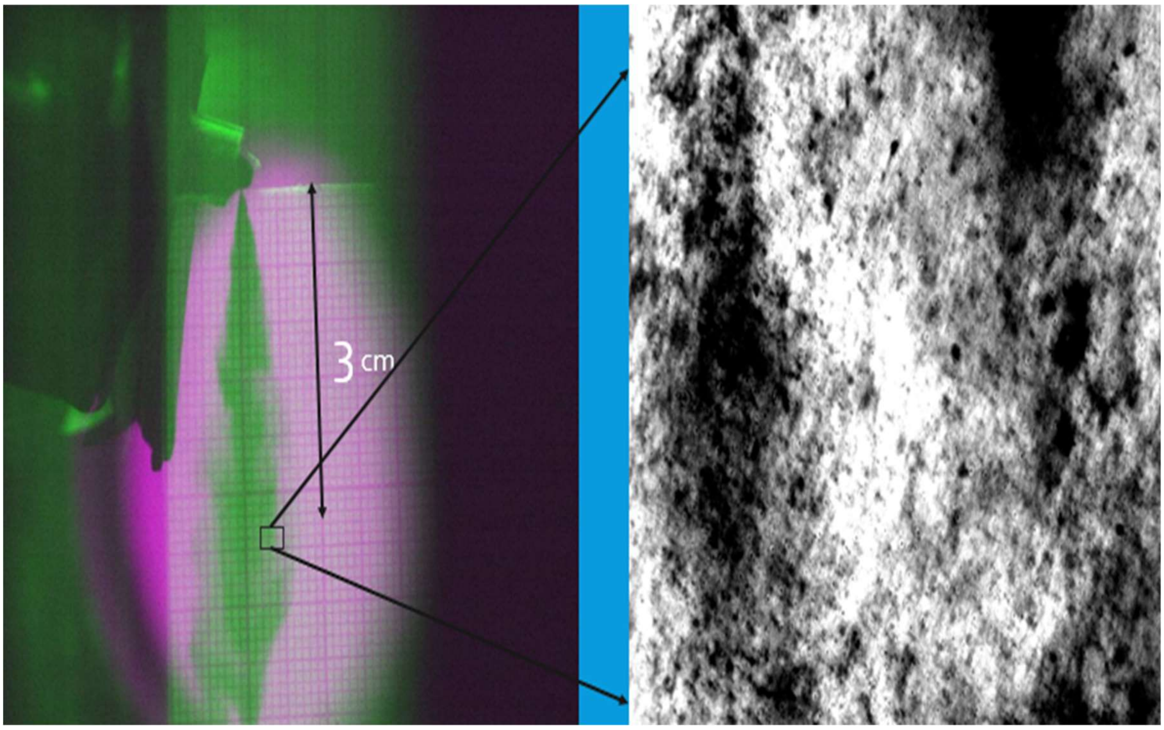

Figure 7: Typical spray image at 300 µs after SOI showing PDIA measurement

Then PDIA algorithm uses an adaptive threshold that adjusts the threshold to each spray image according to the modal image intensity. The selection of region along the spray for PDIA imaging depends on two factors: a) high signal to noise ratio and b) minimum light attenuation by spray droplets. The region of near nozzle is not selected due to presence of ligaments as shown in the figure 8. Similarly, the region at the spray tip cannot be recorded due to very small droplets and presence of mist. Therefore, a region 3 cm below nozzle and 2 mm away from central axis of spray is considered due to optimum signal to noise ratio and minimal light attenuation.

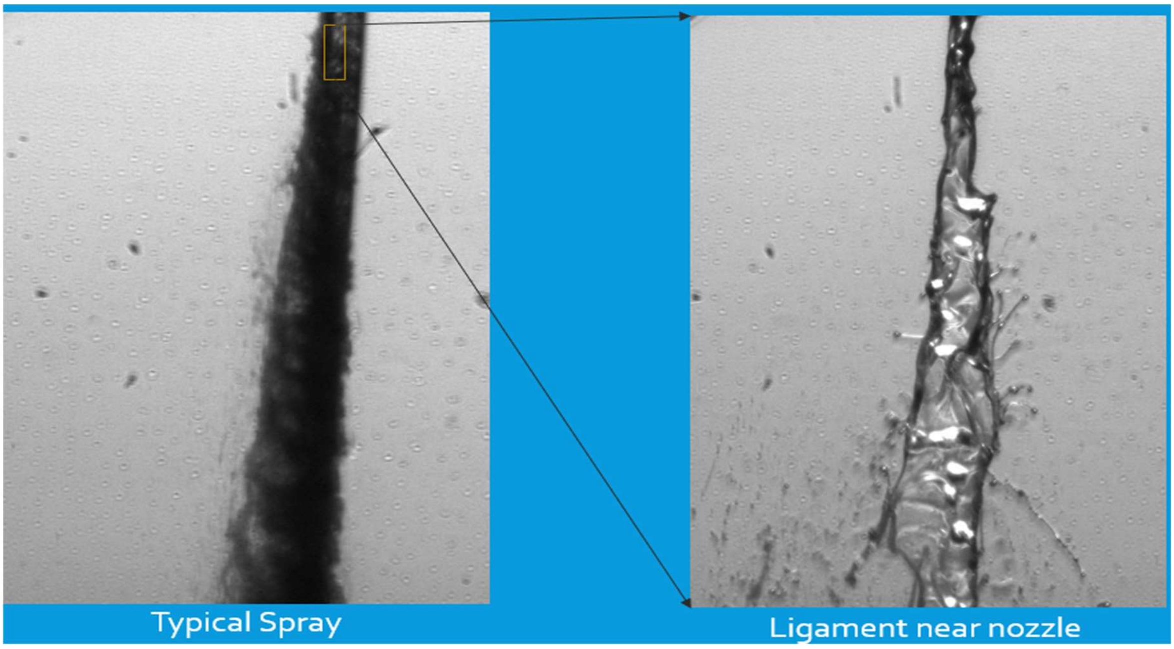

Figure 8: Ligaments present near nozzle of the spray.

The corresponding PDIA image of that region is shown in figure 7. From figure 7, it is clearly seen that the image comprises of small and big droplets with some background noises. These background noises are suppressed using global threshold as shown in figure 10. Then applying low and high threshold algorithm the droplets in the image are estimated and quantified. The PDIA segmentation algorithm is a novel technique to estimate the size of the droplets in the diesel spray. The accuracy of the PDIA technique is relatively high and combined with SLIPI, the accuracy is significantly improved.

Chapter 5
IMAGE POST PROCESSING

5.1 SLIPI

The 1p-SLIPI approach aims at reconstructing the SLIPI image from just one modulated sub-image. It is based on extracting the amplitude of the modulation superimposed on the singly scattered photons. The approach used in known as spatial lock-in algorithm, which has been demonstrated for Rayleigh scattering thermometry of flames [12, 13]. In this algorithm, illustrated in figure 9, the fundamental frequency (denoted as the "first order") of the incident illumination is deduced from the Fourier image.

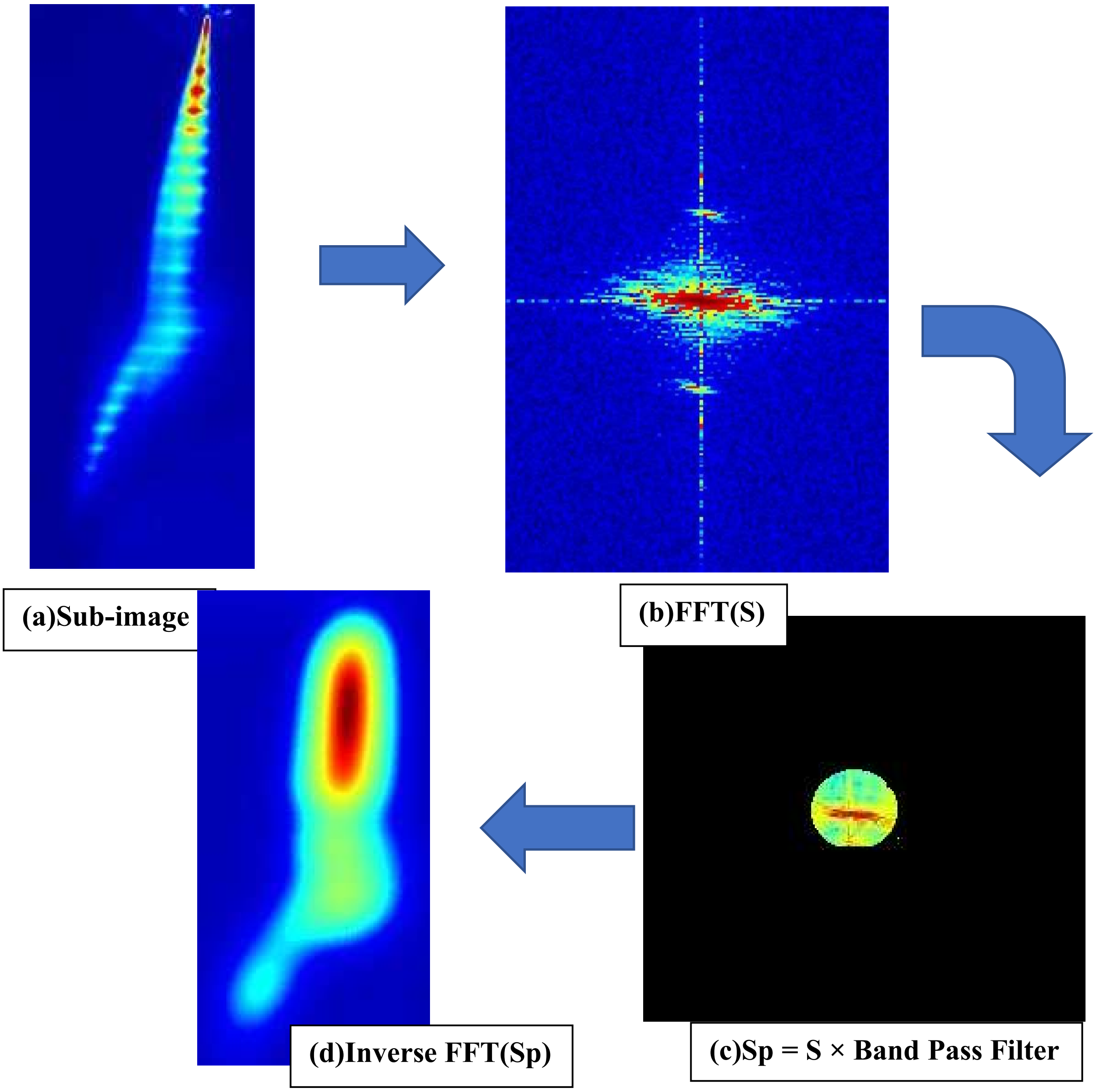

Figure 9: Illustration of SLIPI image post processing. **a, b** Modulated sub-image and its FFT, respectively. **c** Results of the multiplication and **d** is the Inverse Fourier transform.

Using this known frequency value, two reference signals (90° phase shifted from each other) are constructed. Then, both vectors are multiplied with each column of the sub-image matrix. Because of this multiplication, in the resulting matrix, all the modulated terms of the column data are demodulated, while the non-modulated "zeroth order" experiences a shift in frequency. As a result, in the Fourier plane, the unwanted frequency components are kept far from the origin while placing the desired frequency of the modulated signal at the center. Applying a Gaussian low-pass filter to this rearranged image matrix permits the retrieval of only the modulated components in the acquired image.

The resulting SLIPI image, after the 1p-SLIPI post-processing, losses the original spatial resolution of the recorded sub-image. The spatial resolution is also compromised, because the probed sample cannot be fully illuminated with one-phase structured illumination. Thus, to further improve the spatial resolution of the processed image, it is important to illuminate the sample with as many "line patterns" as possible in a given full field-of-view of the image.

5.2 PDIA

The PDIA uses a segmentation thresholding algorithm for the quantitative analysis of droplet or particle images. The image analysis algorithm must account for image-to-image intensity variations. Variations in light attenuation caused by fluctuations in the particle/droplet number density or large variations in the size range of droplets within the field of view may also cause non-negligible image-to-image intensity variations. In order to distinguish the discs or droplets from the illumination background within the image a threshold is applied. The applied threshold will be set at a grayscale level that lies between the two peaks which correspond to the disc/droplet (smaller peak) and image background (larger peak) respectively. The algorithm then effectively scans across the image pixel by pixel and, based on the set threshold level, determines which pixels correspond to the background and those which correspond to the particles or droplets. The diameter measurement in PDIA is based on the area estimate of the shadow image which, for perfect spheres is straightforward.

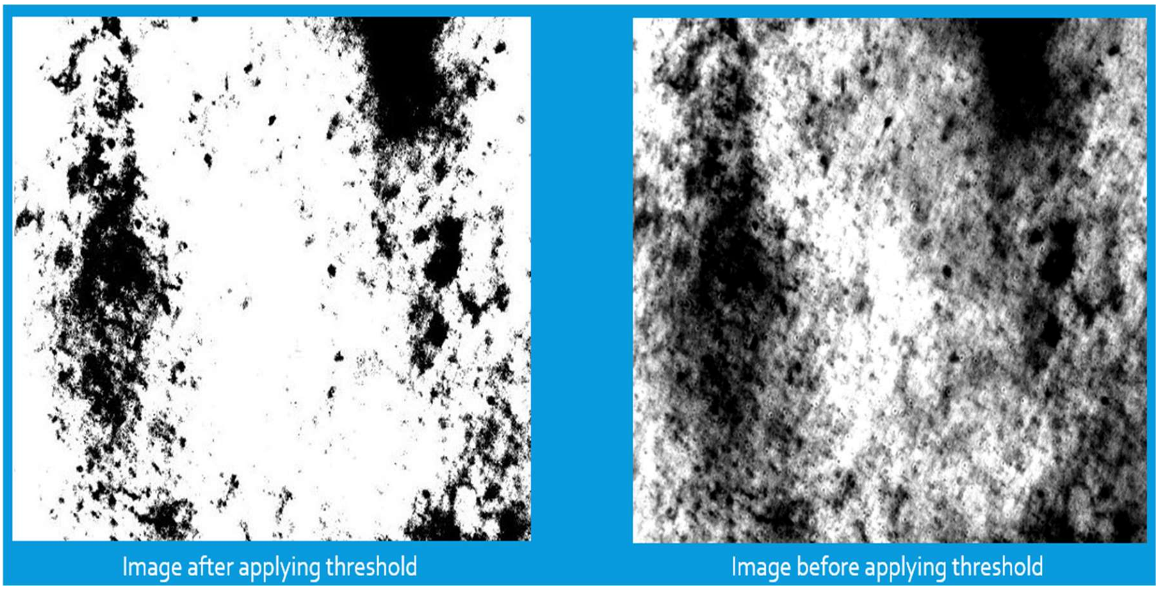

Figure 10: Illustration of PDIA images before and after applying thresholding

The image analysis technique also permits the sizing of non-spherical droplets where the diameter for a droplet of arbitrary shape, D_a is based on the equivalent circular area as given by Eq. (1):

$$D_a = C\sqrt{4A/\pi} \qquad (1)$$

where A is the total number of pixels and C is the microns/pixel calibration. In the present study, the sphericity, S is defined as the ratio of the diameter of the non-spherical droplet, Da to the diameter of the droplet based on the equivalent circular perimeter, D_p defined in Eqs. (2) and (3):

$$D_p = CP/\pi \qquad (2)$$

$$S = D_a / D_p \qquad (3)$$

where P is the number of pixels on the perimeter of the object.

Chapter 6
RESULTS & DISCUSSION

Planar liquid volume fraction distribution is obtained using SLIPI-PLIF and liquid volume fraction at a point from the PDIA technique. The fluorescence signal is proportional to the volume of the liquid (V_F) present in the total pixel volume (V_T) [2,14]. For PDIA, a set of 300 images have been recorded and utilizing threshold algorithm, a histogram of droplet vs diameter, is obtained for each image. The histogram assists in calculating liquid volume by providing number of droplets and their corresponding diameter. Now, by using Patterson globe [11], depth of field is calculated and the volume of the field of view is estimated. Then, LVF is calculated for each image and finally their average is taken. Once the LVF is calculated from PDIA, now we will employ it to estimate the calibration constant. Since LVF is directly proportional to fluorescence intensity of spray. For this purpose, the SLIPI-PLIF image is taken and the small section where PDIA is calculated is considered.

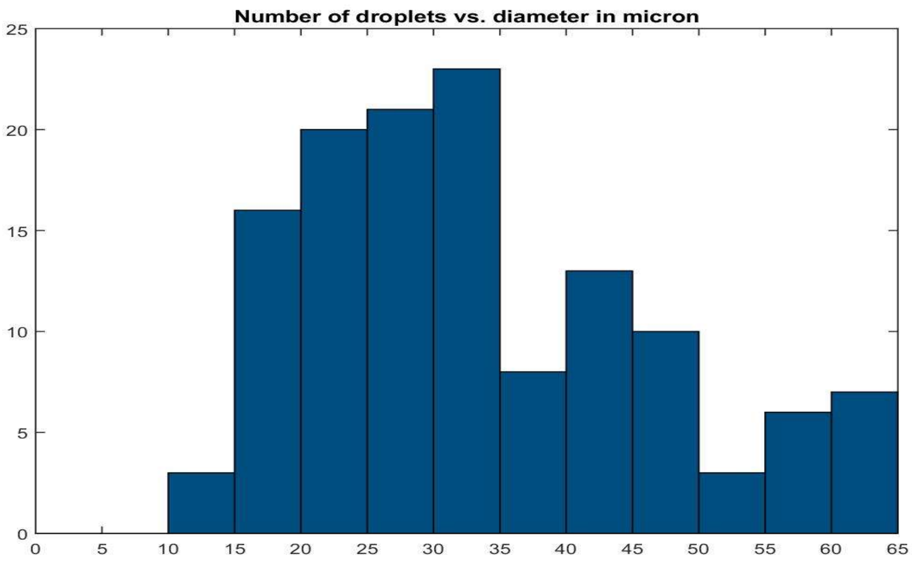

Figure 11: Histogram of droplets vs diameter

The mean intensity of that section is calculated in MATLAB. Then the LVF calculated earlier is divided by this mean intensity and the calibration constant is obtained. Then this calibration constant is multiplied by SLIPI-PLIF image and LVF of the spray is achieved.

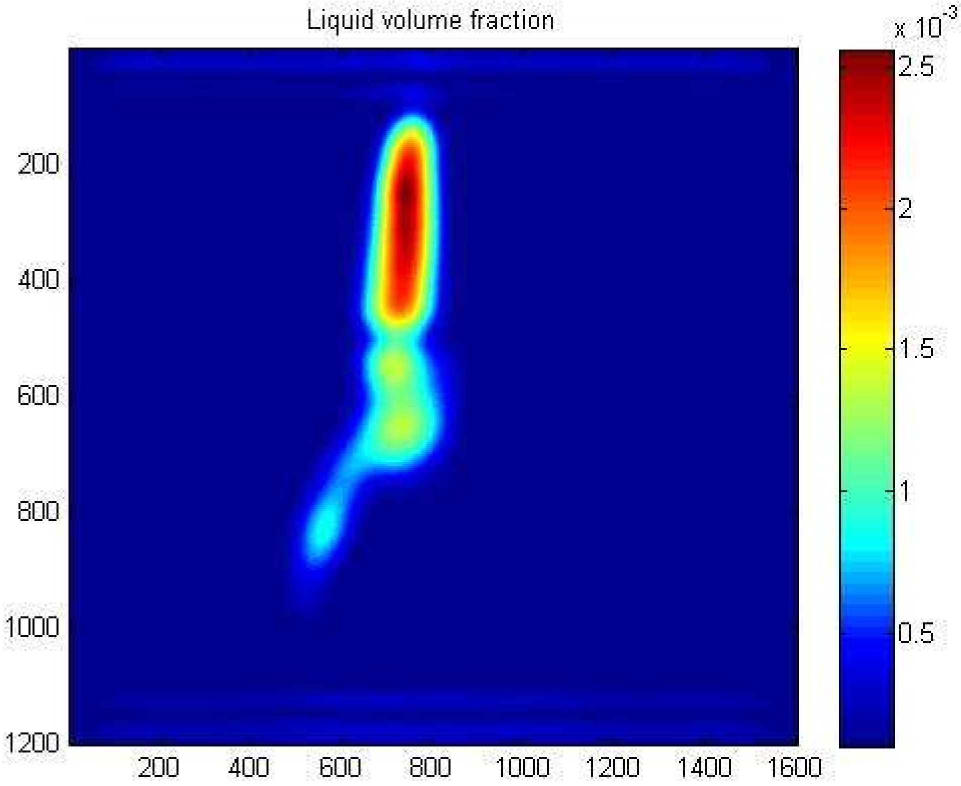

Figure 12: Liquid Volume Fraction of Diesel spray

There are certain limitations to SLIPI-PLIF technique. The accuracy of this technique depends on the spatial frequency of line patterns. Higher the frequency of line pattern, higher will be the accuracy. But multiple scattering and other optical losses limits the upper boundary of this frequency and utilizing lower frequency line pattern implies more extrapolation leading more errors in the results. Thus, the spatial frequency for your application have to be selected meticulously.

Chapter 7
CONCLUSION

A novel and simple methodology is developed for extracting quantitative planar liquid volume fraction in dense sprays. The liquid volume fraction distribution is obtained using a combination of SLIPI-PLIF technique and PDIA technique. The drop size distributions, obtained using the PDIA technique at the periphery of the spray, showed a large number of droplets around 30 to 40 microns for diesel spray. The liquid volume fraction of diesel is very high near the nozzle and it reduces at the periphery and at the spray tip of the spray due to high atomization. The SLIPI technique is used to reduce the error in the conventional PLIF signal due to multiple scattering. The errors due to laser sheet scattering, absorption of the laser sheet and auto-absorption in the SLIPI–PLIF signal are corrected using the numerical model.

The conclusions of the study are as follows:

a. The location for PDIA measurement has to be optimized by selecting a region such that it should have minimum light attenuation and high signal to noise ratio.
b. In PDIA, the threshold must be selected meticulously. Detection of droplets and their sizing essentially depends upon the threshold.
c. The selection of spatial frequency of grating has to be optimized.
d. High spatial frequency line patterns are exterminated by multiple scattering due to highly dense spray.
e. Low spatial frequency line patterns cannot be selected due to its vulnerability to errors.
f. The concentration of dye should be optimized. Low concentration will not produce adequate fluorescence signal and high concentration will lead to extinction of laser light.
g. The Liquid Volume Fraction of dense spray such as diesel can be quantified with high accuracy using SLIPI-PLIF and PDIA technique.

Chapter 8
SCOPE FOR FUTURE WORK

The Liquid Volume Fraction of spray can be qualitatively correlated with temperature. So, for establishing a quantitative correlation between temperature and Liquid Volume Fraction. The temperature along the spray can be calculated using SLIPI-PLIF imaging technique. Once the temperature distribution is achieved, an empirical relation between temperature and Liquid Volume Fraction can be established.

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