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# Experimental Study of Liquid Fuel Spray Characteristics and Atomization - A Review

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*Abstract*— Spray atomization is nothing but the conversion of bulk liquid into a large number of small droplets (i.e. a spray) which generally occurs when we inject fuel through a nozzle. The combustion performance and emissions are mainly influenced by the atomization, evaporation and velocity of the fuel droplets and mixing of fuel with air. The major challenge is to get control on NOx and CO emission which minimizes the efficiency of combustion process, temperature distribution etc. Laser diagnostics system is now emerging as a powerful tool for the investigation of fuel characteristics. Proper atomization of fuel always leads to complete combustion. In this study the effect on fuel spray characteristics such as SMD, velocity of fuel droplets, vorticity, centricity, air entrainment by changing the injection pressure and mass flow rate was studied with the help of laser diagnostics system. Sauter Mean Diameter (SMD) is average droplet diameter. Co-flow means addition of excess air to the surrounding of spray to enhance the air entrainment to get proper/complete combustion of fuel droplets. Therefore it becomes extremely important to understand the fuel spray dispersion under different conditions of pressure and fuel flow rate.

***Key words:*** Non Reacting Spray, Spray Cone Angle, Co-Flow Velocity, SMD, Particle Image Velocimetry, Shadography

## I. INTRODUCTION

Combustion is branch of science that affects almost every aspect of human activities. Nowadays diesel engine related research, driven by environmental issues and global energy demand, is becoming more and more important. 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 [1]. The process of injecting a diesel fluid into the thermodynamic behavior of a working fluid (air or gas) has been a priority in the research of the phenomena that occur in combustion systems. 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 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.

Spray combustion plays a major role of the total energy requirement of the world due to its numerous applications. The basic process of spray combustion comprise the injection of fuel, breakup of fuel into small droplets called atomization.

A spray flame is different than the gaseous flame because the composition of fuel is not uniform. The droplets in the spray are polydisperse in nature and all droplets having different velocities. This nature of spray flame affects the propagation and stabilization of flame. The essential stages involved in spray combustion are atomization and burning of liquid fuel. The fuel is transmitted from the fuel storage tank by a fuel handling system such as pumps, filters and then atomized with nozzles in which the fuel is atomized into small droplets. These droplets are usually injected directly into the combustion chamber where they burn. This mixing process is controlled by the geometry of the combustion chamber, the spatial distribution and momentum of the injected spray, the direction and momentum of the air flow and the influence of any flame stabilization devices. Consequently the atomizer and combustion chamber should be designed as an integrated unit rather than as independent items. Understanding of detailed process of spray combustion required the adequate knowledge of burning of individual droplets because spray flame is nothing but the combined burning of individual droplets. It also required the knowledge of droplet size distribution and all processes from conversion of bulk liquid to droplets. Fig 1.1 shows the breaking of liquid jet in the form of droplets.

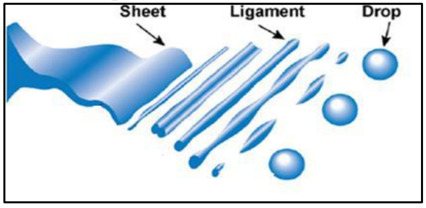

Fig. 1: Breaking of Liquid Jets

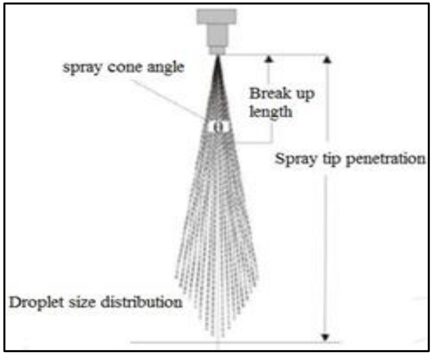

Fig. 2: Physical Parameter of Diesel Spray

The diesel spray can be defined with the following physical parameters as shown in fig 2[1].

- Spray tip penetration
- Spray angle
- Break up length

### *A. Liquid Measuring Techniques*

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].

- Particle Imaging Velocimetry
- Optical Diagnostics
- Laser Doppler Anemometry
- Phase Doppler Anemometry
- Planar laser Induced Fluorescence

## II. LITERATURE SURVEY

### *A. Combustion Regimes*

N. A. Chigier and C. G. Mccreath [2] investigated that the combustion of sprays involves simultaneous heat, mass and momentum transfer and chemical reaction. The main factors affecting the combustion of spray droplets are drop size, composition of the fuel, ambient gas composition, temperature, pressure and the relative velocity between the droplet and the surrounding gas. The solution of problems concerning flame stabilization, rates of combustion, formation of carbon and pollutants and radioactive properties of flames requires detailed knowledge of droplet trajectories and rates of burning of drops, together with a statistical description of the drops in the spray with regard to size and spatial distributions. Other important practical problems such as carbon formation and deposition on combustion chamber walls are affected by both spray characteristics and air flow patterns. This review is an attempt to correlate more closely those factors affecting combustion of single droplets which are relevant to spray combustion and to point out the extent and significance of aerodynamic interaction with sprays. Also included is recent information concerning models of spray combustion [6].

Later on E. Babinsky [3] investigated about modeling size distribution and he found that liquid atomization is the process of converting bulk fluid into small droplets. There are two physical quantities associated with a given drop, its diameter and its velocity. So if we divide the fuel droplets into classes, where each class consists of a drop whose diameter is within range of a given diameter D, so by counting number of drops it is possible to construct a histogram of that class. The continuous sequence of histogram is the probability density function of the drop size. It is also possible to construct area, same case is repeated for velocity [3].

C. Bekdemir [4] study about the region of fuel spray and he stated the important regions as

#### *1) Spray Regimes*

Diesel engine sprays are usually of the full-cone type. This means that in the idle mode the fuel is blocked from the upstream side of the nozzle and during injection the core of the spray is denser than the outer regions.

#### *2) Breakup Regimes*

The disintegration of liquid jets is described by two main mechanisms. The first mechanism is the breakup of the intact liquid core into droplets and is called primary breakup. This mechanism is characterized by the droplet size and the breakup length, which is defined as the length of the intact liquid core. The second mechanism is the breakup of droplets into smaller ones, which is called secondary breakup. Here the size of the droplets is a characteristic parameter. Breakup length and droplet size are dependent on the properties of the liquid and the surrounding air with relative velocity between the liquid and the surrounding air being one of the important property. [4].

### *B. Evaluation of Droplet size distribution and velocity using different optical system*

T. Berg, J. Deppe et.al. [5] investigated on spray and they compare the same results using different measurement technique. They applied all three measurement techniques (PDI, PIV and Shadography) are applied to analyze droplet diameters and velocities at three positions in the spray. Fig 3 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. The droplet size distribution, the diameter of maximum frequency is 37 µm independent of the sizing technique.

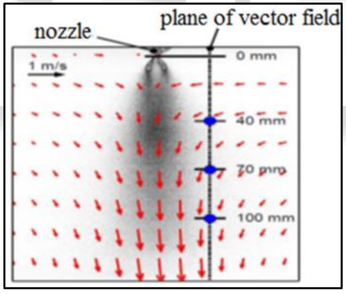

Fig. 3: Positions of measurement and flow field from PIV investigation [5]

However, discrepancies are observed in the graphs for both the small and the large droplet, particularly for the diameter range from 10 µm to 20 µm. According to the results from PDI, the spray tends to exhibit a bi-modal droplet size distribution with a minor peak at 11 mm, which is more pronounced but slightly shifted to larger droplets at 70 mm and 100 mm (graphs not shown here). Neither IMI nor Shadography are able to resolve this phenomenon, since the optical setups are optimized for droplet diameters larger than 20 µm.

Mayur J Sathe, Iqbal H. Thaker et al. [6] studied the visualization about the flow structure. They measures the shape, size, velocity and acceleration of bubbles using shadography, and liquid velocity measurement obtained using PIV/LIF with fluorescent tracer particles. Measurements were performed in a narrow rectangular column at high local gas hold up to 10% with wide variation of bubble sizes (0.1-15 mm). A 2D discrete wavelet transform (DWT) was performed on the liquid velocity field to visualize the flow structures in the bubbly flow. Further, the slip velocity of individual bubbles was obtained from the DWT filtered liquid velocity field. The results are compared with the slip velocity correlations reported in literature for single bubbles rising in quiescent water. The comparison shows the difference in slip velocity of single bubble and bubbles rising in swarm. The scale wise decomposition obtained from DWT was also used to quantify the liquid velocity field in terms of wavenumber spectrum [6]

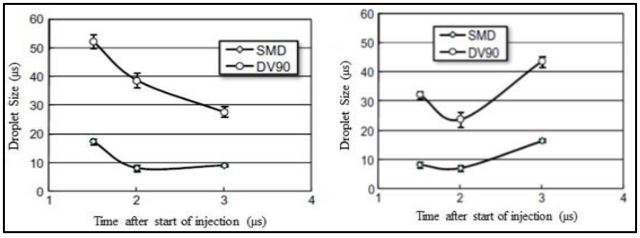

Fig. 4: Spatial droplet size distribution [7]

Tie Li, K. Nishida et.al. [7] work on spray atomization droplet size distribution, velocity distributions of drop at 1 bar and 4 bar injection pressure. The instruments used in this study include the laser diffraction based method for droplet sizing, the laser induced fluorescence particle image velocimetry (LIF-PIV) technique for analyzing the spray and ambient air flows, and the two-wavelength laser absorption scattering (LAS) technique for measuring the concentrations of liquid and vapor phase sprays. Also they studied the time require for ignition. Under ambient pressure 1 bar, both the SMD and DV90 decrease with time proceeding. Under ambient pressure 4 bar, however, these two parameters experience a decrease and then increase up to a larger value. As shown in fig 4, under ambient pressure 4 bar, the line-of-sight measuring volume just passes through the spray leading edge at 1.5 µm. The droplets at the spray leading edge with high penetrating velocity at early time could have encountered stronger resistant force by the ambient air under the higher ambient pressure, resulting in relatively fine atomization.

Fig. 5 shows the velocity distributions of spray droplets and spray-induced ambient air flow at 3.0 µm, under two ambient pressures (a) 1 bar and (b) 4 bar. Here the velocity distribution of spray droplets was obtained by the PIV measurement of the droplets, while that of ambient air flow by the LIF-PIV measurement using a pair of fluorescent images of tracer particles. At some location velocity vectors are missing in the sprays, this is a due to that a threshold was set to cut off some unreasonably high velocity vectors owing to the uncertainties in the PIV measurements in the high density zones of spray droplets.

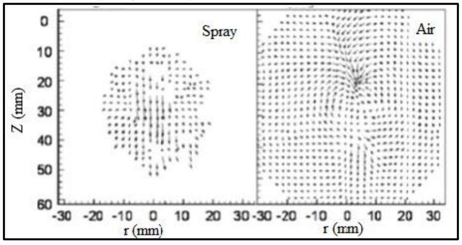

Fig. 5: Velocity distributions of spray droplets[7]

At pressure 1 bar while two vortex-like structures can be found for both the spray droplets and ambient air flow, the vortex structures of the ambient air flow locate about 5 mm upstream compared with those of spray droplets. This discrepancy might be due to the difference between the penetrating velocities of spray and induced air flow. Strong air entrainment into the spray occurs at the spray tail zones, while there are the highest velocity at the center zones between the two vortex structures for both droplets and ambient air. In addition, zones near the spray axis show significantly greater velocity than peripheral zones.

### *C. Effect of spray cone angle, spray tip penetration and vorticity*

S.N. Soid, Z.A. Zainal, [8] they also studied on spray and combustion characteristics using optical techniques in internal engines. Their study investigates better ways of controlling the combustion process, thus ensuring optimum performance and minimum emission levels produced during the combustion process.

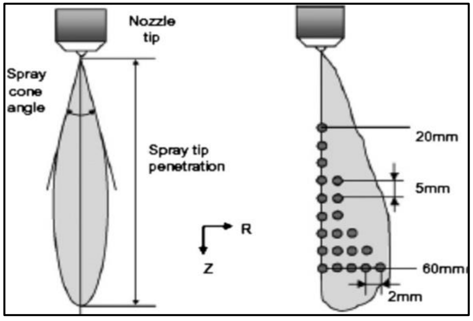

Fig. 6: Spray Characteristics [8]

Initially 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 is as shown in fig.2.4. As the liquid jet leaves the nozzle, it becomes turbulent and the outer surface of the jet breaks up into droplets. They concluded that as the nozzle tip moves away, the mass of air within the spray increases, the spray diverges, its width increases, and the velocity decreases. The longer tip penetration and larger cone angle are desirable for maximum air utilization and better combustion due to the increased spray area [8].

S. Ghaemi, P. Rahimi et. al. [9] also studied on all these parameters and they mostly concentrate on spherical shape of droplets i.e. centricity. They conducted experiments at various locations. From the shadography results they concluded that the non-spherical droplets formed because of aerodynamic forces and droplet collisions and also it demonstrate that higher numbers of non-spherical droplets are observed at the near nozzle region and far radial locations [9].

### *D. Literature review reveals that*

- In practical situation droplet interactions has been approached in three ways droplet array theory, droplet group theory, and spray theory.
- The longer tip penetration and larger cone angle are desirable for maximum air utilization and better combustion.
- SMD, spray cone angle, temperature, pressure, break-up length needs to be studied properly. Both breakup length and droplet size are dependent on the properties of the liquid and the surrounding gas. At least as important is

the relative velocity between the liquid and the surrounding gas.

- The droplets size and density effect remains unchanged because though the diameter of droplets at the center zones is smaller, the number density is significantly higher than at the peripheral zones.
- Small droplets are generally more likely to have spherical shapes in comparison to larger droplets due to dominance of surface tension forces resulting in a low Weber number.

### *E. Problem Definition*

Combustion with the liquid fuels involves large amount of instability as compared to gaseous fuel due to polydisperse nature of droplets, also the velocity of droplets is not uniform. As we required better efficiency of IC engines, it is necessary to avoid the instability. Thus it is required to study the spray characteristics like droplet size distribution, velocity of droplet, vorticity and centricity along the spray.

### *F. Objective*

1) To analyze the droplet dynamics parameters from velocity distribution to vorticity distribution.
2) To study the effect of co-flow velocity on spray characteristics.
3) To study the air entrainment and its effect on droplet velocity.
4) To study the droplet size distribution and centricity with the help of laser diagnostics system.

## III. 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. For continuous flow it is necessary that the flow field should have proper number of particles that can illuminate the laser light and it should be small enough to keep the flow field invariant. These particles, called seeding particles, are externally mixed with the flow. This technique is called Particle Image Velocimetry (PIV).

### *A. Particle Image velocimetry*

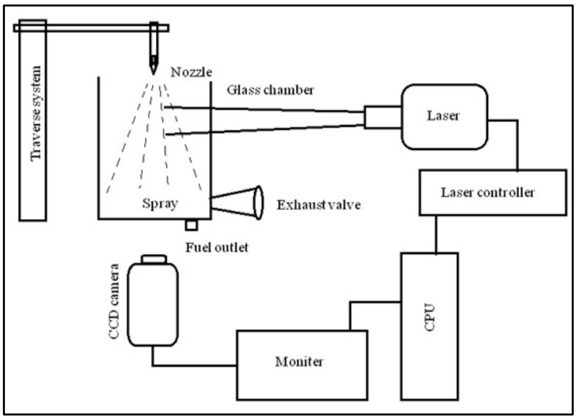

Fig. 7: Setup of PIV

It works on a simple principle. For example, to find the velocity of a river, we put a light weight object on the river and measure its displacement in a given time interval. Similarly, in PIV, we take two images back to back in a given time interval and then find the displacement of the individual particle and hence the velocity field is determined. If the PIV (fig.7) is to be used for measuring velocity of droplet in a liquid spray, then the external seeding of particle is not required, because the droplet of the liquid will give enough illumination to be captured by camera.

#### *1) Scaling*

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 carefully 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.8.

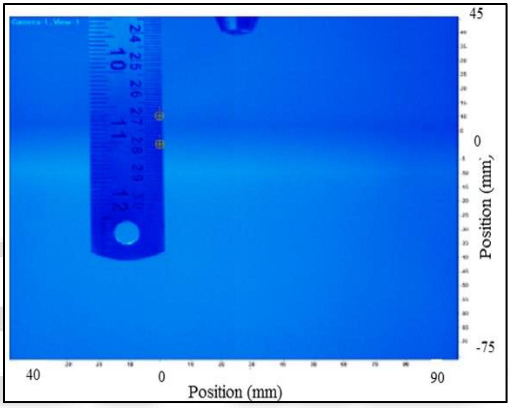

Fig. 8: Scaling of PIV

#### *2) Field of View*

It is nothing but the fuel droplet portion comes under camera picture. The preferred camera viewing direction is perpendicular to the light sheet. Optimize the optical access to the field of view. If possible avoid optical distortion by windows between camera and flow. Clean windows from contamination and use high quality camera lenses. In this we have to select the exposure time i.e. dt and the frame mode. Also we need to select a suitable factor of magnification to resolve the flow structures. Remember that the particles within one interrogation window must move uniformly in the same direction and the same distance to assure a good contribution to the correlation. [6]

#### *3) CCD Recording Modes*

For the image recording CCD cameras can operate in different modes. Any CCD camera can operate in a single frame mode.

- Single frame mode
- Double frame mode

a) Single Frame Mode

The scattered light from first and second exposure of the particles is recorded in one image. The complete image is subdivided in so called interrogation windows and each window is evaluated by auto correlation. The single frame mode allows to take a single exposure of the camera. In this case the CCD exposure time can be specified and the integration is limited by the electronic shutter. This mode can be used for the acquisition of images at a given exposure time with light or synchronized to a pulsed light source. Depending on the selected options this single frame can record the light of a single light pulse or of two light pulses.

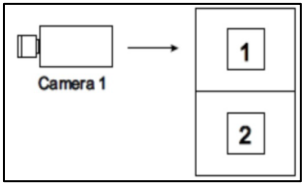

Fig. 9: CCD Recording in double mode [11]

b) Double Frame Mode

The scattered light from first and second exposure of the particles is recorded in two different images. The complete image is subdivided in interrogation windows and each window is evaluated by cross correlation.

– Light Sheet Adjustment

In order to minimize systematic errors and the out-of-plane loss of particles the maximum velocity component should be parallel to the light sheet. Select a suitable height for light sheet depending on the distance between sheet optics and field of view and size of the field of view in order to minimize the loss of light as shown in fig.10.

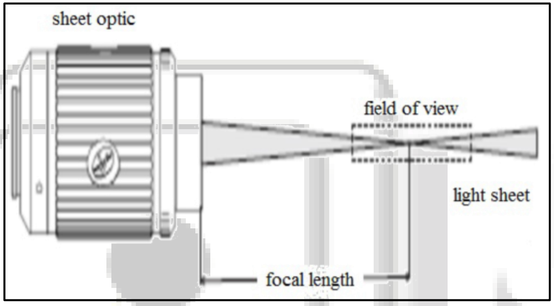

Fig. 10: Light Sheet Adjustment

– Adjust pulse separation “dt”

The pulse separation has to be adjusted in a way that the particle image shift “dt” is in the interval given by the resolution of the system and the maximum allowable particle shift. The particle image shift can be recognized in the particle image itself when you zoom into the image and toggle between the both frames.

– Recording

In addition to the standard option of the Recording dialog there are specific options available that go alongside with a PIV project. Following are some steps that should be carried out before recording.

1) The laser must be switched on.
2) The laser beam must be adjusted to illuminate the flow inside the experiment.
3) The camera must be focused on the particles illuminated by the laser.
4) Timing: Correct trigger source and suitable pulse separation dt.

– Processing

Use the test processing button to apply the operations in the sequence to one image and the start processing to the selected image range. The processing dialog can also be used for vector processing to calculate further derivatives like average velocity, vorticity etc.

### *B. Shadography*

Another technique which is used for measuring the fuel parameters is Shadography. The shadowgraphy technique is used to visualize particles (e.g. droplets from a spray or bubbles in liquid). The technique is based on high resolution imaging with pulsed backlight illumination (see fig.3.5).This technique is independent of the shape and material (either transparent or opaque) of the particles and allows to investigate sizes down to 5 µm using an appropriate imaging system and light source [10,11]

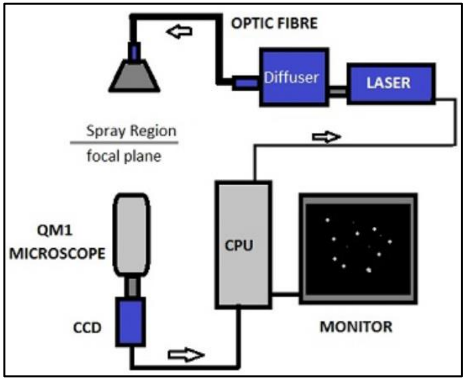

Fig. 11: Setup of Shadography

Following are the equipment’s necessary for shadography.

#### *1) Microscope*

The detection system for the particle master is generally a long distance microscope with a SVGA camera to resolve particles down to 5 µm. The setup for particle sizing via shadow imaging requires two optical accesses to the experiment which have to be in line with the probe volume. Taking into account the overall length of the detection system, consisting of lens, connection tubes and camera, a free distance of about 1.5 m is required. The same applies to the illumination unit with laser and diffuser optics, adding up to a total length of the optical setup of at least 3 m. To acquire the images of individual particles, an appropriate imaging system has to be used. Regarding the required minimal working distances and spatial resolution long distance microscopes or macro lenses are recommended in combination with a regular CCD camera. The choice of imaging lens mainly depends on the working distance.

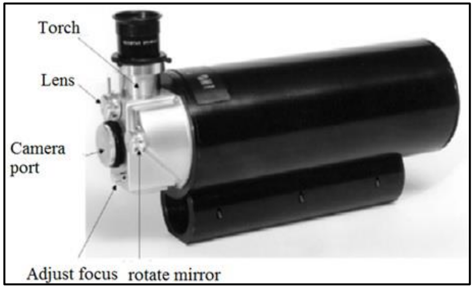

Fig. 11: Long distance microscope torch

Fig. 11: Shows the long distance microscope. The QM1 is a mirror based long distance microscope. It has a working range of 560 mm (22 inches) to 1520 mm (66 inches) (subject plane to front element). The QM1 includes two selectable ports, one to connect a camera, one to either connect an eye piece or a torch. The torch can be used to roughly define the focal plane. Additional there are two knobs on the back:

– A small one below the camera port which adjusts the focal plane. One above the camera port to put an additional lens into the optical path of the eye piece (The lens does not affect the optical path to the camera).

- One beside the camera port, which rotates a mirror which either sets the eye piece port as output or the camera port (rotate mirror). The QM1 allows to use additional magnification lenses between camera and microscope. Figure shows the dependence between magnification lens, working distance and field of view. If the knurled knob for the focus control is completely screwed in, the focal plane should be in a distance of about 1.5 m. Once the focal plane is found, it can be adjusted to the intended plane by rotating the knob for the focus. When the focus is adjusted with the torch, it has to be re-adjusted a little bit to the camera.

### 2) *Diffuser*

In PIV we generally used a laser beam to analyze the flow parameters, but in shadography we used a diffuse light instead of direct laser.

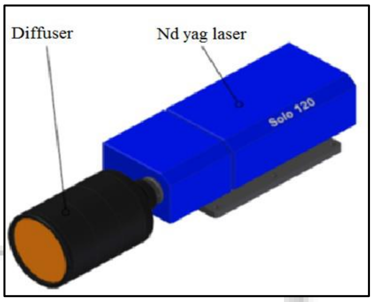

Fig. 12: Laser and diffuser optics for background illumination.

The diffuser used in this setup is fluorescence plate diffuser with a diameter of 120 mm to diffuse the light on spray droplets. Its light indicates the collection angle of the detection optics, though it may be required to reduce ambient light to visualize the light of the torch, e.g. on a piece of white paper. The schematic is shown in fig.12. The illumination unit, i.e. the fluorescent dye plate, should be placed in the optical path of the detection system, ensuring optimum illumination of the area covered by the light of the torch.

### 3) *Scaling*

In the following the scaling of the imaging system for particle sizing is described for the QM1. This description is also valid for other lenses. To scale the camera image, a plate with a grid of defined separation is provided with the particle master. The plate has a scale of 5 mm divided into 200 lines as shown in fig. 13 and 14 respectively.

Fig. 13: Scaling Plate

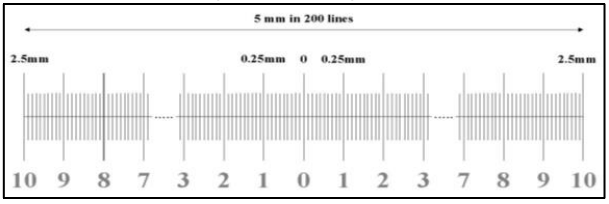

Fig. 14: Lines and corresponding distances of the scaling target

### 4) *Recording*

The particle sizing includes the inversion of the recorded shadow image. Furthermore, detection limits of the individual particles are depending on the intensity contrast between the area covered by the particle and the illuminated background. In an ideal measurement, the illumination is spatially and temporally uniform and may be defined precisely. However, usually some in homogeneities can be observed in the background. Therefore, a reference image is required, which may either be recorded separately or calculated individually during the evaluation.

- Experiment images: These are the actual images which contain the backlight illuminated particles. The path and file names for data storage can be selected automatically or manually by the user.
- Reference images: These images are stored in the properties subfolder and are used during the evaluation of the experiment images. File names cannot be changed. Since the size evaluation is based on thresholds of image intensities a homogeneously illuminated background is important but difficult to achieve. A different solution is to record a reference image which exhibits the same intensity distribution as the experiment images and can be used for normalization.

#### a) Processing

In processing we processed a data set of particle images, the results can be displayed in configurable histograms and scatter plots, finally creating a standardized reporting document containing the statistical data and the diameter histogram. Also the following quantities can be determined.

- Centricity
- Diameter and Volume
- Horizontal and vertical position
- Absolute, horizontal and vertical speed
- Maximum and minimum diameter

## IV. POSSIBLE OUTCOME

It emerges from the review that no technique has yet met all the necessary specifications for sizing drops in the sprays from large atomizers. The spray length and shape are to be well predicted to auto-ignites the fuel droplet. But combustion temperatures stay low, the previously determined general effects of ambient temperature, oxygen concentrations, and turbulence on burning rates for single drops will require to be modified to take into account the location of the flame front with respect to the drop surface in a spray fame. It was also reviewed that the droplet group combustion tends to reduce the gaseous temperature, and that this is caused mainly by the suppression of combustion reaction due to the lack of oxygen and partially by the heat exchange from low temperature droplets (droplet cooling effect). For proper combustion at least two desired conditions should be satisfied.

1) The parameters of the given drop size distribution should be stable i.e. there should not be any small variation in the input conditions of the spray.
2) The distribution should be unique i.e. there should be only set of parameter values to give a good fit to some experimental data.

As this work is in progress so after completion, we will come to know about the fuel droplet parameters such as

SMD, velocity, centricity, vorticity along with various pressure range.

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