LASER INDUCED FLUOROMETRY AND VELOCIMETRY: IMPLEMENTATION OF QUANTUM DOTS AS FLUOROPHORES

Sahithi Kandlakunta, Dept. of Mechanical Engineering, Tennessee Tech University
Mahesh Panchagnula, Dept. of Mechanical Engineering, Tennessee Tech University

ABSTRACT
The characteristics of fuel atomizers have been studied by using a fluorescence optical patternator via establishing a laser sheet illumination of the spray and an image capturing system. Line laser Mie-scattering and fluorescence imaging technique is used to study the fuel mass distribution, geometrical properties, angle and symmetry in sprays. The proposed experimental setup employs Rhodamine 6G as the fluorophore. A set of filters have been used to reduce the signature from the combustion fire while being able to image the nanoparticles. Experimental results are obtained under the conditions of the fuel with and without being seeded with quantum dots and under both non-combusting and combusting spray conditions. The results from the study are validated against existing volume flux distribution measurements by conventional techniques. Owing to the high luminescence properties of quantum dots, the liquid volume distribution can accurately be determined in an evaporating as well as a non-evaporating spray using this technique. Quantum dots are semiconductor nanoparticles whose emission wavelength can be tuned by the choice of their size. Also their, high luminescence properties are advantageous in a spectrally “noisy” combustion environment.

INTRODUCTION
Combustion processes have wide ranging and important applications in many engineering applications. The behavior of fuel sprays, atomization and distribution of fuel drops in the spray field, fuel-air mixing and amount of pollution are of importance in the combustion process. The fuel spray characteristics play a major role in working of many practical combustion devices such as Diesel engines, Rocket engines, gas turbine engines, Oil-fired boilers, furnaces and process heaters. A swirl is imparted to stabilize the spray pattern. An efficient and pollution free combustion requires an intensive study of atomization, vaporization, diffusion, mixing and chemical reactions. The spray combustion process typically results in a 3-dimensional, turbulent, and multi-phase flow field. Hence the study and measurement of this flow field is a formidable task. Reliable diagnostic techniques for measuring the various flow parameters are invaluable to engineers. Fuel volume and area distribution are among the most important in this respect.

Various studies have been made to measure the spray characteristics using Laser Induced Fluorescence (LIF) by an optical patternator. A study of fuel mass distribution, geometrical properties, angle and symmetry of spray was done by planar scattering and planar fluorescence imaging technique and to measure Sauter mean diameter everywhere on the plane of spray [1]. Flow visualization techniques were used to observe overall qualitative features of the sprays to delineate the effect of airflow pattern upon droplet transport processors under burning and non-burning conditions. The droplet mean size was found to increase with axial distance along the centre line and spray boundary [2]. The fuel temperature at various locations of the spray was calculated by 2-dimensional measurements of liquid phase temperatures in fuel sprays by comparing the images from a CCD camera for known temperature and at combustion temperature [3]. A technique to measure interstitial velocities in refractive index matched porous media called Fluorescent Particle Imaging Velocimetry (FPIV) has also been employed [4].

The precursor to the reaction zone in a non-premixed spray combustion process is a region where the liquid is being atomized and brought into contact with the oxidizer stream. The atomization and mixing efficiency bear large influence on the combustor performance. The oxidizer stream in most instances is a swirling air stream that can be characterized by turbulence measurement techniques. The fuel is typically delivered by a spray nozzle which introduces drops into the swirling oxidizer stream. The mixing characteristics of these two streams and more specifically fuel concentration distribution is proposed to be measured by Laser Induced Fluorescence. We propose to utilize a combination of these two
diagnostic techniques to help understand the fuel distribution in the near nozzle region of a swirl stabilized burner.

The current paper presents one-dimensional hotwire data for a single phase swirling flow at various axial and radial locations in the flow field. This data is presented as axial mean velocity and turbulence profiles. A study of mean drop size, mean liquid surface area and mean liquid volume density across the spray field is performed using Laser Induced Fluorescence (LIF). A procedure for preparation of quantum dots is discussed. Its future application is in the combustion process for higher temperature evaporating spray conditions using LIF.

**EXPERIMENTAL APPARATUS**

The experimental apparatus consists of a two-dimensional Hot wire anemometry system and a prototype Laser Induced Fluorescence system. The construction and calibration of these systems is discussed hereunder.

**Hot wire anemometer**

A model 1015C two-dimensional hot wire anemometer is used to measure air mean velocity and turbulence. It consists of a small resistance element which is heated and controlled at an elevated temperature. The hot wire anemometer works on the principle of Wheatstone bridge. The sensor forms one of the resistors with high temperature coefficient while the other resistors have fixed resistances. As the fluid flows over the sensor, its temperature decreases, decreasing its resistance and thus unbalancing the bridge. The amplifier in the anemometer supplies the voltage required to bring the sensor back to its original temperature, thus balancing the bridge. The voltage supplied is recorded using a data acquisition software, specially configured for this purpose in LABVIEW®. The voltage supplied is proportional to rate of cooling and thus the velocity of flowing fluid. The voltages from the bridge are recorded at the rate of 1000Hz.

**Hot wire Calibration procedure:**

The 2D hot wire to be used in the current experiment has to be calibrated. The bridge voltage (E) and the velocity (U) are proportional. There exist a linear relationship between $E^2$ and $\sqrt{U}$ given by $E^2 = A + B\sqrt{U}$, where A, B are calibration constants. The calibration constants are found by plotting calibration curve with various mean velocity values taken at different flow rates using a pitot tube and manometer and corresponding voltages taken from the data acquisition system. For the 2D hotwire both the wires should be calibrated separately. Hence there are two sets of calibration constants. The voltage values from the anemometer can be converted to corresponding velocity values using these calibration constants. The calibration setup consists of the following:

1. **Flow chamber:** A variable speed DC motor for the creation of a uniform velocity profile in a tube, with a variac arrangement to vary the flow rate.
2. **Plexiglas Tube:** A tube of 20in length and 4in diameter with an arrangement to accommodate the hot wire probe and pitot tube such that both face the same flow at equal axial velocities.
3. **Honeycomb structure:** To streamline the flow.

The hotwire traverse mechanism is placed perpendicular to the burner traverse and in between burner and exhaust chamber. The burner has a diameter of 6.5cms which is used as the non-dimensionalization length scale. The burner is equipped with 6 slots radially placed at a distance of 1.2cms from the centre of the burner to create a swirling flow from slots and axial flow at the centre. The fuel supply line is cut-off so that burner operates only as a blower. The burner is started and traversed till it is 10mm (x/D = 0.15) from the probe. At
this burner position, the probe is traversed starting from one side of the burner where there is no turbulence recorded on an oscilloscope till it reaches a similar point of near zero turbulence on the other end in the increments of 6.25 mm. The voltages at each of these locations are recorded and converted to velocity. The procedure is then repeated for different burner locations in increments of 10mm till burner is 80mm (x/D = 1.23) from probe. The mean velocity and root mean square velocity components thus obtained are plotted with respect to non-dimensional probe location (r/R, where R is the burner radius) at different burner x/D positions. It must be mentioned that the hot wire system used is capable of measuring two-dimensional velocity components and turbulence. However, we present in this paper, only axial velocity (one-dimensional) data as a test case for further analysis and study.

**Experimental setup for LIF:**

The setup consists of:

1. **Laser Excitation Source**: An Argon ion laser of 514 nm is setup on a table such that it passes through the spray.
2. **Atomizer system**: A solution of a fluorescent dye Rhodamine 6G (approximate concentration of 0.4% by mass) is mixed with water and sprayed through a nozzle.
3. **CCD Camera**: Mounted on a stand at the level of the laser beam to capture the elastic scattered light as well as the fluorescent emission by imaging without and with a filter in place respectively.

Rhodamine 6G has an absorption line near 514nm which causes it to fluoresce in the green. When this beam passes through the spray field, it excites the molecules of the fluorescent dye by absorbing the photons and radiates it as fluorescence. Accompanied by the fluorescence emission, there is an elastic scattering of the photons by the drops. While the former process produces green light proportional to mean drop volume distribution, the latter produces blue light proportional to mean surface area distribution. We wish to take advantage of these two modes of scattering and measure mean drop size distribution based on these two measurements. The diameter distribution in the spray field can be estimated by the ratio of intensity of orange light to the intensity of blue light.

**Quantum dots procedure:**

Rhodamine 6G which was used as the fluorophore in the present pilot study will chemically break down at elevated temperatures (~50°C). In order for us to be able to make similar LIF measurements in evaporating high temperature sprays, we wish to employ CdSe quantum dots (QD) as the fluorophores. The procedure fabricating these QD’s was adapted from the online research site of University of Wisconsin [5]. 30mg of Selenium and 5ml of Octadecene are added to a 10ml round bottom flask over a stirrer hot plate in a fume hood. A syringe is used to add 0.4ml of Triocylphosphine to the flask from its Sure-Seal bottle. The solution is stirred by adding a magnetic stir bar and warmed till the Selenium is dissolved completely. The solution is cooled to room temperature and stored in a sealed container. This stock solution can be for five preparations of quantum dots and can be stored for one week.

13mg of Cadmium oxide is added to a 25ml round bottom flask clamped on a heating mantle. A dry pipette is used to add 0.6ml of Oleic acid and 10ml Octadecene to this flask. A thermometer capable of measuring 225 degrees C is inserted. This Cadmium solution is heated up to 225 degrees C. A dry pipette or syringe is used to transfer 1ml of room temperature Selenium solution to the Cadmium solution. As the “cooking time” progresses the solution changes color from pale yellow to bright red due to increase in particle size. This also causes the peak emission wavelength to become red-shifted as can be observed from emission spectra data in figure 1. As the cooking time increases, the full width at half maximum of the spectra are also observed to increase indicated that the solution is no longer mono-disperse. The solution is transferred to a beaker with liquid nitrogen when it is of the desired color. The liquid Nitrogen is used for quick quenching of the solution.

The emission spectra are recorded to find maximum wavelength peak by placing the sample solution in a beam of 400nm wavelength light. The quantum dots thus synthesized can be mixed with the fuel and used with a UV laser excitation source in the burner to study the fuel spray characteristics at elevated temperatures.

**RESULTS AND DISCUSSION**

Two classes of results are presented from this study – hot wire mean velocity and turbulence data as well as LIF data from a spray system.

Figure 2 is a plot of non-dimensional mean axial velocity component (U) profile normalized by the centerline velocity at that axial location versus non-dimensional radial probe position at different burner locations (varying x/D). The highest peak corresponds to the maximum velocity at the centre of the burner and the two smaller peaks near approximately r/R=1...
corresponds to the contribution of axial momentum from the swirling air ensuing from the swirler slots. A decrease in the velocity is observed as the burner is moved away from the probe till approximately x/D = 0.61. At this point there is an increase in the peak value at the mixing layer and the values decrease gradually thereafter till it is almost a smooth curve at an x/D = 1.23. The small asymmetry in the velocity profiles recorded for x/D between 0.62 and 1.1 could possibly be due to a radial misalignment of the probe in the flow field.

![Figure 2: Mean axial velocity profiles for various axial positions](image)

Figure 2: Mean axial velocity profiles for various axial positions

Figure 3 is a plot of the absolute centerline velocity versus x/D. As can be seen from this figure, the centerline velocity exhibits a nearly linear decay as for the case of a classical turbulent round jet [6].

Figure 4 is a plot of fluctuating axial component of velocity (U'_rms) normalized by the centerline mean axial velocity at that axial location versus nondimensional radial probe position (r/R) for various burner positions (x/D). The peaks correspond to regions of high shear and turbulence production in the mixing layers while a decrease in fluctuation is observed at the centre of the burner. The peak turbulent intensities are observed to decrease as the burner is moved away up to x/D = 0.62, at which position there is a slight increase and a gradual decrease thereafter till it is a smooth curve at x/D = 1.23.

![Figure 4: rms axial velocity turbulence radial profiles for various axial positions](image)

Figure 4: rms axial velocity turbulence radial profiles for various axial positions

The hotwire data will be used in conjunction with the laser induced fluorescence based drop volume distribution measurements to characterize the mixing behavior of the two streams in the near field region.

**Laser Induced Fluorescence imaging results**

Laser induced fluorescence technique was developed following the technique proposed by Sankar et. Al. [1] to simultaneously measure mean drop size distribution, mean drop surface area distribution and mean drop volume distribution in a spray. As mentioned before, the spray was illuminated by an Argon ion line laser source while the scattered light and fluorescence emission was recorded by a camera placed at an angle of approximately 20° to the laser line (See figure 5 (a) and (b) for the raw images obtained thus). Figure 5(a) is the raw image obtained from elastic scattering of the laser by the drops as they pass through the spray, while figure 5(b) is a filtered image of the spray wherein only the fluorescence wavelength was sampled. As was mentioned before, figures 5(a) and 5(b) are representative of the mean drop surface area and mean drop volume distributions respectively. It must be mentioned that the image from the fluorescence emission (figure 5b) appears orange owing to the color of the filter placed in front of the lens to filter out the laser wavelength. By taking the ratio of the two raw intensities obtained from these images, one can obtain a measure of the mean drop size distribution and more specifically the Sauter Mean Diameter, as it is a ratio of the total drop volume divided by the total surface area.

\[
D_{SMD} = \frac{\sum D_i^3}{\sum D_i^2}
\]  

(1)
The raw images shown in fig 5 are first corrected for perspective and scatter angle, as the light scattered from the farthest part of the spray from the camera is at a higher angle of scatter relative to the light scattered from the nearest part of the spray. Subsequent to these corrections, the intensity is averaged normal to the laser position.

![Raw images of scattered light and fluorescent light](image)

**Figure 5: Raw images of (a) Scattered light and (b) Fluorescent light**

Figure 6 is a plot of the mean drop size, surface area and volume distributions versus a dimensionless width of the spray. As can be observed from figure 6, the surface area distribution demonstrates a bimodal distribution while the fluorescence intensity distribution shows a peak in the center. The resulting drop size distribution is scaled to arbitrary units and plotted in figure 6. The drop size distribution shows larger drops in the middle of the spray while smaller drops are observed near the edges. Thus we have shown the feasibility of using a compound Mie-scatter and LIF technique to simultaneously measure drop size, drop surface area and drop volume distributions.

**CONCLUSION**

In conclusion, we have developed a LIF based technique to simultaneously measure spatial drop size, drop surface area and drop volume distribution. This technique will be used in conjunction with the data from a three-dimensional hot wire system to understand the near field mixing behavior in an evaporating spray.

**REFERENCES**


