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TWO-DIMENSIONAL MEASUREMENTS OF INTERNAL SPRAY FEATURES AND MACROSCOPIC CHARACTERISTICS

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ABSTRACT

A novel laser speckles based imaging technique for droplet size, shape and velocity visualization and measurements of injection sprays in DI diesel engines has been demonstrated in order to contribute to a reduction of the parameter optimization time as well as for a more accurate optimization of the parameters of modern electronically controlled diesel engine injection systems.

The technique allows the characterization of the macroscopic behavior of a diesel spray. For current high pressure injection systems it is essential to determine the internal spray features as droplet diameter, density, shape, temperature and velocity distributions and their evolution with time.

Experimental results are provided from laser speckles based 2D imaging technique for visualization and measurements in the near nozzle region of injection sprays and to illustrate the scattering behavior of droplets at different locations in a complex spray flow field.

1. INTRODUCTION

Sprays are crucial in a number of industrial areas today, such as in combustion and ink jet printing. In particular, the need to develop internal combustion engines to comply with tightening emission legislation has led to increased interest in sprays.

Achieving a clean and efficient combustion process in current Diesel engines requires a proper fuel-air mixing process, which is a direct consequence of the fuel spray development and fuel-air interaction inside the engine combustion chamber. The high-pressure Spray dynamics is quite complex. The spray structure and behavior are clearly influenced by several parameters related to the environment in which the spray is injected (gas density, temperature, geometry of the combustion chamber, etc.) and the parameters inherent to the Diesel injection system (nozzle geometry, injection pressure, injection rate shape, etc.).

A large number of experiments have been performed by several researchers over the past decades to improve the understanding of the process and to isolate the parameters controlling the spray behavior. The experiments have tried to provide either empirical correlations or simple models to explain the spray behavior under different situations on the basis of the experimental evidence.

However, the models for in-cylinder spray breakup, atomization, and vaporization still do not produce satisfactory results in situations that are significantly different from those to which the models were fitted. To develop the models further, we need diagnostic tools, e.g., for studying droplet velocity, droplet size and shape distribution, and droplet temperature.

Within this frame, a novel 2D laser speckles based imaging technique for droplet size visualization and measurements of injection sprays in

- DI Diesel engines and in a high temperature, high pressure combustion cell was developed in order to contribute in case of DI Diesel engines to a reduction of the parameter optimization time as well as for a more accurate optimization of the parameters of modern electronically controlled Diesel engine injection system in DI Diesel engines

- High Pressure – High Temperature Combustion Cell for experimental investigations of processes governing Diesel fuel injection and combustion as fuel spray penetration and atomization, fuel-air mixing, spray ignition and combustion. Based on the experimental investigations, new physical models describing fuel injection and combustion processes are developed and validated.

We are currently investigating a technique which requires in the case of a DI diesel engine only a minimal modification of the DI diesel cylinder head by a small enlargement of the glow plug bore and allows fuel spray investigation under all engine operating conditions.

Furthermore the recording of two separated full frame droplet images within a short time interval for advanced cross-correlation analysis allows for droplet image velocimetry [1]. Data obtained simultaneously in the speckle field for droplet size and droplet velocimetry measurements of a spray in a high pressure-high temperature cell will be presented.

During our investigation it came apparent that the detection of the droplet shape are of importance, since the droplet size can be significantly affected by the nonspherical shape of the droplets. In this paper therefore we describe acquisition of experimental speckles light-scattering data of deformed droplets in a high pressure-high temperature cell.

Determination of spray tip penetration, cone angle, and air entrained by the spray are usually performed on the basis of imaging techniques. Different optical devices are commonly used, such as conventional and high speed photography [2], line-scan cameras and CCD and intensified cameras, with both conventional optics and speckles endoscopes. Also, a large range of illumination devices, from Xe lamp [3] to continuous or pulsed lasers [4] are used.

A common drawback of all these techniques, and in general of all imaging techniques, is that the results depend strongly on the limitation and accuracy of the droplet size detection. Moreover, the determination of the spray boundaries present peculiar difficulties owing to the two-phase nature of diesel spray, so that the spray edges are often not clearly defined. Thus the accurate measurement of the spray angle (which, being a basic input parameter for current phenomenological predicting models depends strongly on the criteria followed to determine the spray contour) is especially difficult.

The purpose of this study is the development of a system to detect spray boundaries in direct-injection Diesel speckles spray images for measurement of the spray tip penetration and cone angle by use of a digital speckles image-processing technique. This system must work with images from different facilities (which provide different experimental approaches to actual engine behavior): High pressure high temperature Cell and running engines. The components used (lenses, mirrors, diffusers, windows, light guides, etc.) are quite unique on the particular tests, and in all cases it is possible to reduce the same configuration between different analogous experiments (position of the camera and illumination system, camera parameters, etc.).

2. INSTRUMENTATION AND EXPERIMENTAL TECHNIQUE

2.1 HIGH PRESSURE – HIGH TEMPERATURE COMBUSTION CELL

A special high pressure - high temperature combustion cell has been designed and built in cooperation of our lab and the Paul Scherrer Institute (PSI). Experimental conditions in the cell are consistent with those found in Diesel engines, but in addition, an even broader range of parameters like gas pressure and gas temperature can be realized. As Figure 1 shows, the cell is ideally suited for the application of laser diagnostic techniques through a high degree of optical access. The main steps for a combustion cycle involves the supply of heated and pressurized gas in front of the intake valve. A work cycle starts with a single rotation of a cam shaft which opens the intake valve. Subsequently the fuel is injected and combustion occurs. At the end of the cycle the gas leaves the cell through the exhaust valve. This process can be repeated of up to one per second.

2.2 LASER SPECKLES BASED IMAGING TECHNIQUE

The droplet detection system was designed in order to visualize droplets in the range of 2.0 μm to 100 μm. The mechanical dimensions had to be kept very small, especially in order to fit as well as into the enlarged glow plug bore of a DI diesel engine. The design of the probe tip as comprises a quartz rod window within a steel tube, a laser illumination quartz fiber and the collecting optics, located in the middle of the quartz rod lens. Since the probe tip can be rotated around the steel tube axis and varied in the protrusion depth, the detection area can be chosen in dense or dilute spray regions. In the setup of the probe tip, the maximum fiber diameter is 1000 μm. The speckle size can be varied as mentioned in [1], by changing the aperture respectively the fiber diameter.

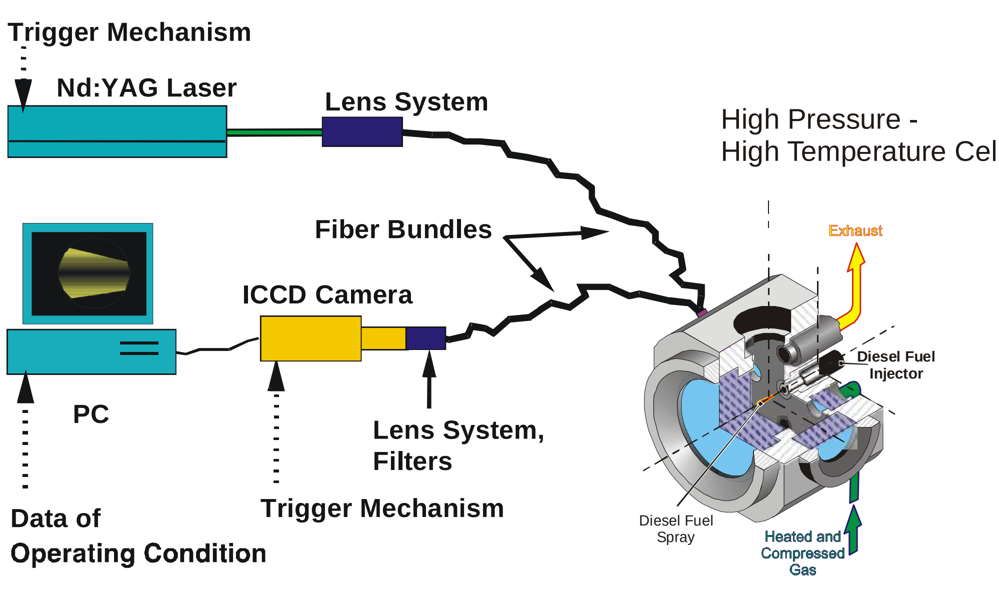

Fig. 1: Experimental setup with optically accessed High Pressure – High Temperature Combustion Cell

3. EXPERIMENT

3.1. DROPLET SIZE DETECTION

The experimental arrangement makes use of the speckle pattern produced by a coherent monochromatic source such as a laser after passing through a lightwave guide. In order to avoid droplet traces due to droplet movement a frequency-doubled (532 nm) pulsed Nd:YAG laser served as a coherent light source. The images of the reflected/refracted zones of injection spray droplets are collected through a segmented optical linkage and a zoom objective to a fiber coupled intensified ICCD camera. With a search routine the image is scanned for connected pixel groups with high intensity values, i.e. white dots that represent the reflection/refraction zones on droplets due to the speckles field illumination, for the determination of number, size and position in the image [1]. An intensified CCD camera receives the reflected and 2nd order refracted light from the droplets. The imaged rectangular detection area is 338 x 225 μm, respectively 653 x 435 μm. The size of the reflection and refraction zones from the droplet to the corresponding droplet diameter was calculated by a ray-tracing technique. Finally, the droplets sizes and the droplet number (Fig. 2 and 3) of each size class of the whole detection area are determined.

3.2. DROPLET VELOCITY DETECTION

Droplet image velocimetry is an optical measurement technique that allows the acquisition of instantaneous flow fields in a planar cross section. The motion of the reflected/refracted zones of the droplets in a speckles field is recorded by taking a doubly exposed image. The displacement of reflected/refracted images during the time delay between two exposures is directly proportional to the local droplet velocity. The recorded images are analyzed by cross correlation which offers a precise determination of the flow direction. Given the image magnification and the time delay between the exposure one obtains the instantaneous in-plane velocity and velocity fields of the droplets as shown in Figure 2.

3.3. DROPLET SHAPE DETECTION

The spatial distribution of light scattered by a particle, also in certain texts referred to as the two-dimensional angular optical scattering pattern is a complex function of the size, shape, dielectric structure, and orientation of the particle, as well as of the properties of the illuminating radiation (wavelengths, polarization state). Analysis of the scattering pattern can provide a way to characterize the shape, orientation, and structure of the illuminated droplet, and many researchers have exploited this property in various ways. Previous research by the author has explored the potential of scattering pattern analysis for droplet shape and size classification and has demonstrated in non combusting environment how such techniques can be implemented in the described novel laser speckles based imaging technique for droplet size and velocity measurements of injection sprays.

Scattering patterns can cover different scattering angle ranges depending on the light collection geometry used to acquire them. We recorded the examples shown in Figure 3 (see figure 3 description of droplet observation position) by imaging the pattern of light scattered by individual droplets onto an intensified charge-coupled device (ICCD) camera as the droplets interacted with the laser speckles light sheet. In each case light scattered between 5° and 30° scattering angle was captured as a 256 by 256 pixel image. The beam direction is perpendicular to the paper in the center of each image. Each white dot in the patterns corresponds to a single scattered photon, and the images thus represent photon distribution maps of several thousands to several tens of thousands of scattered photons. The images illustrate the wide variations these patterns can assume for different droplet shapes and orientations. It was the potential of spatial light-scattering analysis for droplet shape characterization that initiated the fundamental study of droplet scattering. It also underpins an ultimate aim of this research; namely, to provide an on-line optical means to correct for the errors in measured aerodynamic size caused by droplet deformation.

3.3.1 Experimental Method

As discussed in [1], the detection technique is realized with one small optical access to the combustion chamber mainly based on two reasons. Firstly, because the technique should help to optimize a series engine and therefore only minimum modifications to the cylinder are allowed and secondly, the windows should be as small as possible in order to keep the disturbance of the temperature distribution on the walls and thus the cylinder gas to a minimum. Therefore, the optical access was made through an adapter to the glow plug bore, which holds the probe tip of the detection system. This, however, required a slight enlargement of this bore to the core diameter of the thread (9 mm).

The schematic diagram of the experimental setup in this study is shown in Figure 1. The LSIDS system comprises an illumination and a completely separated detection system which are collinear arranged within the probe tip. The illumination is based on the speckle phenomena of laser light. A multimode quartz/quartz fiber transmits light from a pulsed Nd:YAG laser into the combustion chamber where a speckle pattern is formed. The droplets of the injection sprays interact with the speckle field and as a result the light of reflection, refraction and scattered light is transmitted trough a magnifying lens system, an interference filter and a segmented optical linkage to an ICCD camera using a zoom objective. The main reason for the demand of a pulsed Nd:YAG laser is the short laser pulse (8 ns) that “freeze” the injection droplets in their motion during the laser pulse illumination.

In this paper we consider only the scattered light which allowed the acquisition of spatial scattering patterns from individual droplets in the below 30-μm-size range as they traversed the measurement speckle field over a range of injection conditions both less than and greater than the norm so as to gain a greater understanding of the morphological changes that take place.

3.3.2 Light-Scattering Pattern Acquisition

The beam from the Nd:YAG laser transmits through multimode quartz/quartz fiber, a quarter-wave plate to generate a circularly polarized laser speckle field of elliptical cross section. As each droplet traverses the speckle field, light scattered in the backward direction between angles of 5° and 25° is imaged onto an intensified, asynchronously triggered ICCD camera. The lower angular limit is set by a beam stop, whereas the higher limit is set to avoid shadowing of the scattered light by the lower surface of the injection nozzle. Images from the camera are digitized, displayed, and stored on a computer at a rate of several images per second for later analysis. A trigger signal for the acquisition of a scattering pattern by the camera is derived from a separate diode detector module which receives light scattered at a higher scattering angle than the camera. The rising and trailing edges of the signal from the diode detector, respectively, initiate the camera exposure period.

4. RESULTS

All experimental data presented here were recorded from droplets by a single hole nozzle with a hole diameter 0n 0.13 mm and a length of 0.55 mm. Injection pressure was 500 bar, the injection timing was between 0.6 to 1.0 ms.

The 2D drop size, drop shape, and velocity are shown as plots versus time after injector electronic trigger in the near-nozzle region. The arithmetic mean drop sizes D10 were calculated and are shown in Figure 2 (left) at different measurement positions.

Discrete radial velocity data are shown in Figure 2 (right). Number histograms for droplet size measurements are shown (Fig.3) for the measurement position, z = 1.0 mm and at the radial position x = 0.1mm.

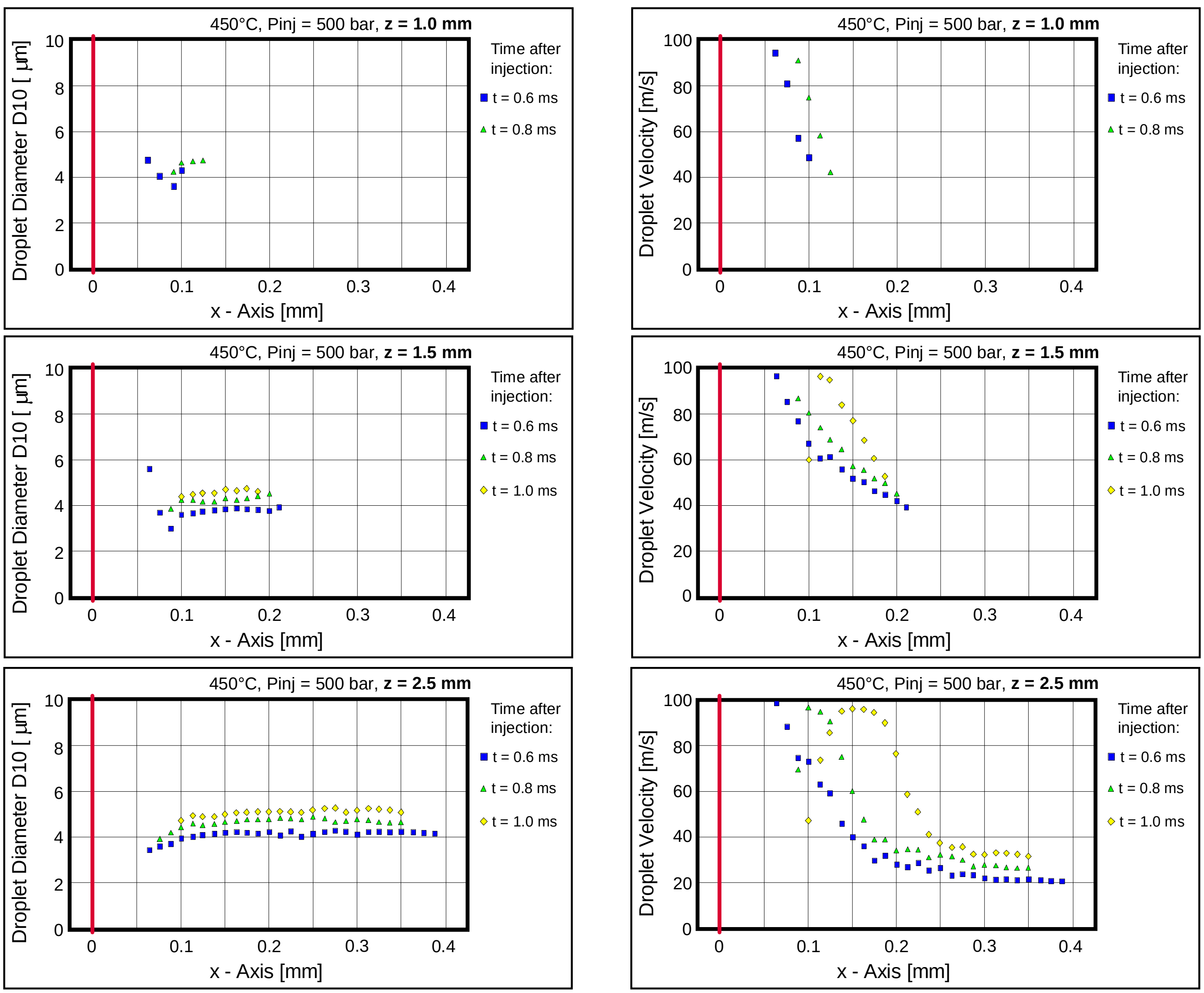

Fig. 2: Radial profiles of the drop size (left) and the velocity (right) over a period of 0.60 and 1.0 ms at measurement locations z = 1.0, 1.5 and 2.5 mm

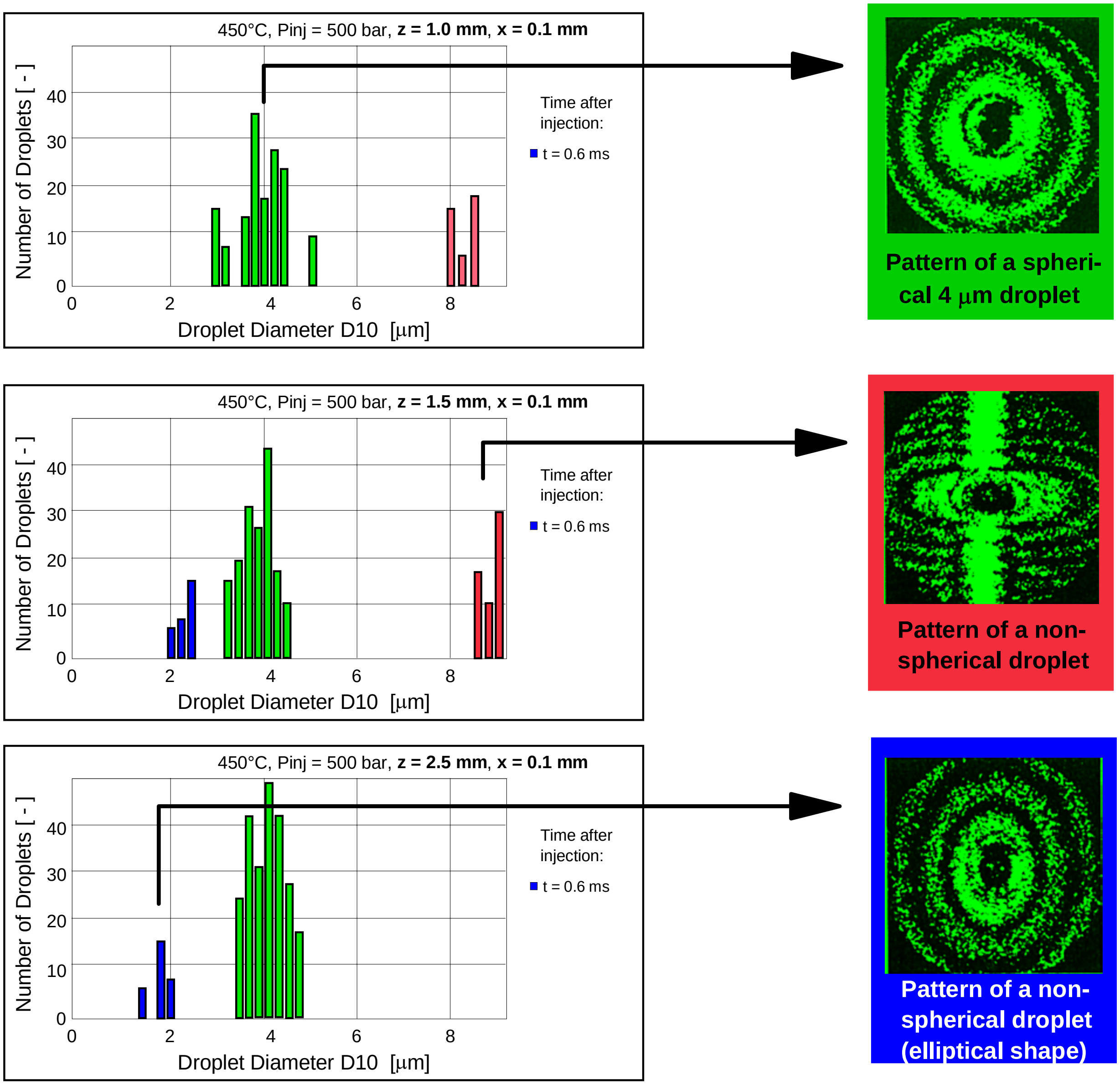

Fig. 3: Drop size distribution (left) and drop shape (right) after 0.6 ms after injection at measurement locations z = 1.0 mm, and radial position x = 0.1 mm

As a result of the experimental investigation it was evident that in region close to the spray orifices, the number droplet size classification showed drastically a reduction of the number droplets and a loss of droplet classes. In view of this study we considered that a certain amount of those droplets in distinct droplet size class are due to the fact, that those may have a nonspherical shape.

When one attempts to measure nonspherical particles of known density, the shape (and orientation) of each particle subjected to the accelerating flow governs the drag force, it experiences and hence affects the measured size. The measurement of liquid droplets is subjected to significant error, because the droplets deform to oblate spheroids in the flow as shown in Figure 3 from the speckles light scattering pattern images for undistorted and distorted droplets.

5. FUTURE WORK

A laser speckles 2D imaging technique was tested to characterize the behavior of a diesel spray. What is of significant interest is the simultaneous diagnostic, allowing the measurement of droplet size, shape, and velocity of complex spray flow fields. Future work will include droplet temperature measurements. A method based on the exploitation of an organc exiplex is discussed in Ref. 5. In this method the intensity ratio of the monomer emission to the exiplex emission was found to be sensitive to temperature. The Technique was successfully applied in fuel droplet temperature measurements[6] and in spray[7] and mixture[8] visualization. In using this technique, one should take into consideration quenching from molecular oxygen in the gas phase and monomer vapor interference as the fuel heats and evaporates.

One approach to temperature measurements that has recently been applied to droplet studies is thermometry that uses thermographic phosphors or laser-induced phosphorescence (LIP)[9]. Temperature measurements that use thermographic phosphors offer a number of advantages, e.g. high accuracy, remote detection, and high signal yield: it is hoped that many problems of infrared thermometry and LIF may be overcome. Furthermore, one advantage of phosphorescence emission compared with fluorescence is that, whereas the latter has a lifetime of nanoseconds, phosphorescence emission is typically in the range of microseconds to milliseconds. The relatively long lifetime is used to prevent interference from scattered light and any fluorescence from other substances that are present in the measurement area. The research so far was only conducted on single droplet thermometry. We intend to extend the existing technique to two-dimensional measurements of droplet temperature under combusting condition in the near future.

6. CONCLUSION

Because fuel sprays are central to modern internal combustion engines, we have stressed the need to characterize the properties of microscopic (geometrical) characteristic and internal spay features (droplet size, shape and velocity).

The experimental data presented in this paper illustrate the complex speckles light reflection, refraction and scattering behavior of droplets, leading to simultaneous two dimensionally, temporarily and spatially resolved droplet size, shape and velocity detection. The reproducibility of the experimental data makes them a valuable resource in the development and testing of spray models. Such models my ultimately provide a route to the rapid characterization to sprays in modern internal combustion engines.

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