Recent Findings of Simultaneous Droplet Size, Shape and Velocity Detection of Injection Sprays in a High Pressure – High Temperature Cell

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To characterize the behavior of a Diesel spray and to extend for current high pressure injection systems it is necessary to determine the internal spray features (droplet diameter, density, shape and velocity distributions) and their evolution with time and the spray geometry accurately, at least in terms of spray tip penetration and cone angle. Experimental results are provided from laser speckles based imaging technique for visualization and measurements of injection sprays and to illustrate the complex speckle-scattering behavior of nonspherical droplets at different locations within the spray.

1. Introduction

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 he 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 four 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.
All these studies consider spray characterization from two different approaches:

1. *Measurements of internal spray features* (droplet velocity and diameter distributions) and their evolution with time by means of interferometric techniques: Fraunhoffer diffraction techniques, phase doppler anemometry and recently, as reported elsewhere by the author, a 2D speckles imaging technique [1].
2. *Determination of macroscopic* (geometric) *characteristics* (spray tip penetration, cone angle, air entrained by the spray, etc.), usually on the basis of imaging techniques.

Within this *first approach*, 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 opti-

mization 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.

Within the *second approach*, 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.).
Finally, as a common drawback to all optical techniques applied to combustion studies, the contamination of the optical access windows affects the image properties, however a special design of the probe tip has been successfully applied to reduce the contamination.

2. Instrumental

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. Droplet detection system

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 an DI diesel engine. The design of the probe tip as comprises an 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.

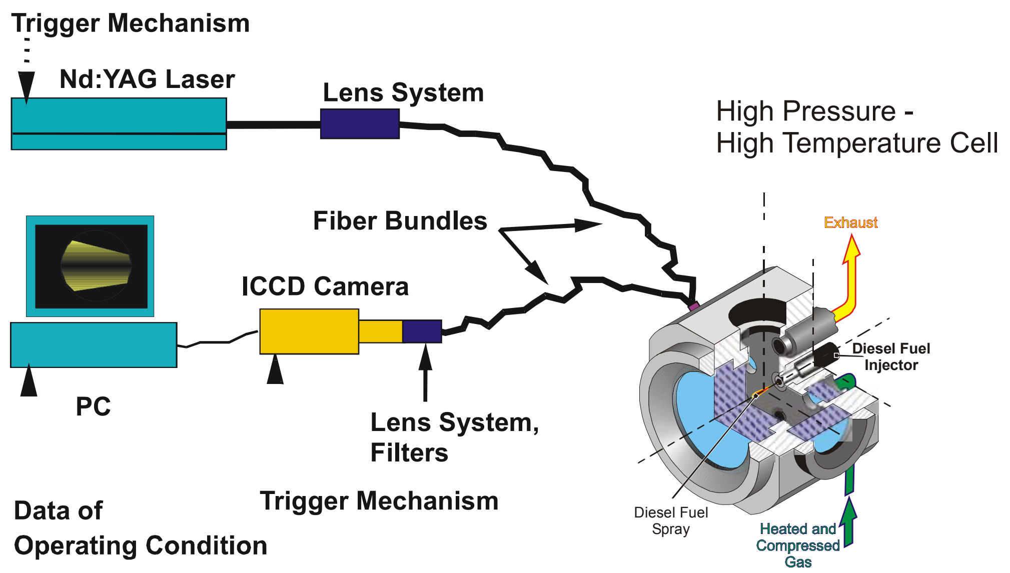

Fig. 1 Experimental setup with optically accessed High Pressure – High Temperature Combustion Cell

3. Experimental

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) 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. Results of droplet size and droplet velocity

Measurements have been performed in the high pressure – high temperature cell in a single hole gasoline direct injection spray. It has been operated at an injection pressure of 500 bar at 400 K. A number of experimental studies were performed during ignition delay at various temperatures (400K …600K) and injection pressures (500 bar … 1000 bar). The imaged diesel spray area (225 μm x 338 μm) lies 1mm above the spray axis. Measurement have been performed at different location from the spray orifice.

As a result of the experimental investigation it was evident that in the 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 missing droplets are due to the fact that those may have an nonspherical shape.

When one attempts to measure nonspherical particles of known density, the shape (and orientation) of each particle subjected to the accelerating airflow governs the drag force it experiences and hence affects the measured aerodynamic size. The measurement of liquid aerosol droplets is subject to significant error (25% undersizing reported in some cases) Because the droplets deform to oblate spheroids in the accelerating airflow. As a result of this deformation, their cross-sectional area increases and they experience a greater acceleration than would be the case with similar-sized rigid spheres. Despite being well reported in the past by Baron [5] and Griffiths et al., [6] there is as yet no systematic method of measuring the degree of deformation experienced by individual droplets in the instrument, and material-specific calibration curves, derived, for example, with gravitational-setting techniques, are invariably required.

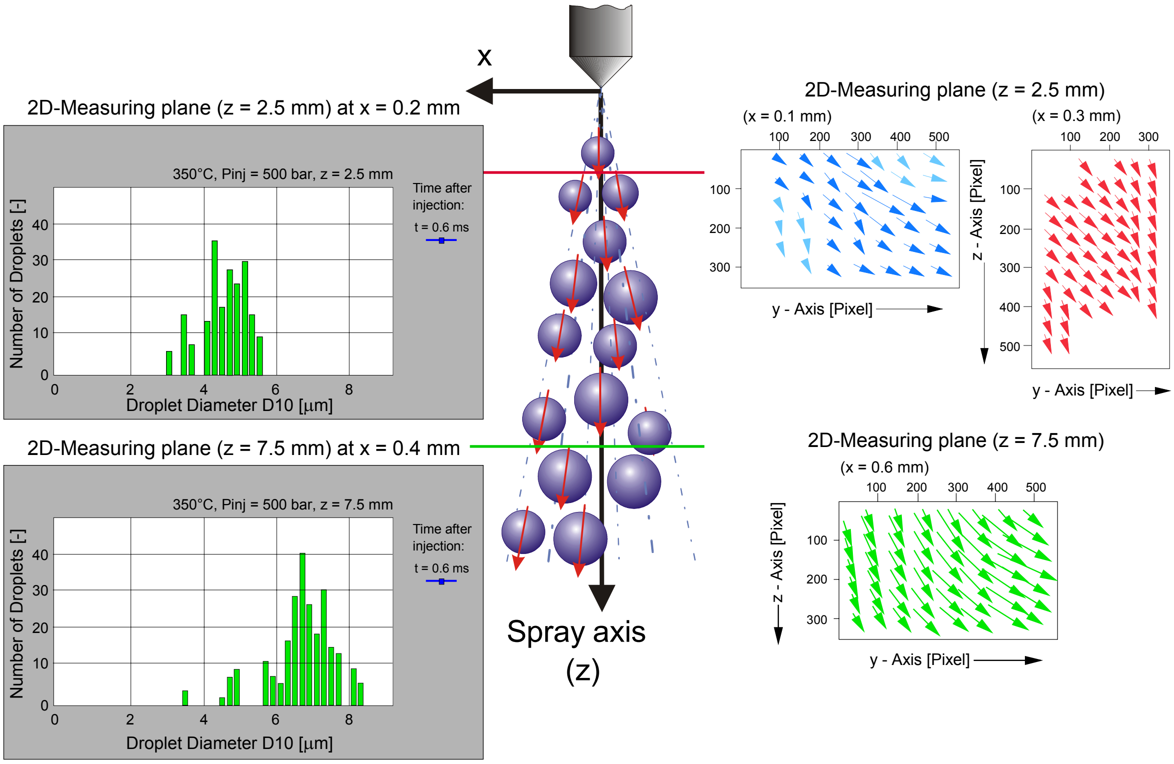

Fig. 2 Droplet size classification (left) and velocity fields (right)

4. Spatial Light Scattering

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 4 (see figure 4 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.

4.1. 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 2. 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.

4.2. 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.

4.3. Experimental Data

All experimental data presented here were recorded from droplets generated by a single hole nozzle with a hole diameter of 0.15 mm and a length of 0.60 mm. Injection pressure was 500 bar, the injection timing was 1.2 ms. Figure 3 illustrates the changes that occur in the spatial light-scattering patterns from individual droplets at different velocity behavior. Scattering patterns was recorded at different radial and axial positions within the diesel spray. Each scat-

tering pattern therefore represents the backward scattering from droplets interacting with the speckles field. The gain of the image intensifier was reduced for larger droplet sizes in the observation plan to minimize optical saturation effects, although these are still present in some of the recorded scattering patterns. The scattering pattern correlates closely with that predicted by Mie Theory for a perfect spherical droplet. The degree of droplet deformation is evident from the increasing ellipticity of the scattering maxima and minima that are evident on the pattern, as shown in Figure 3.
Figure 3 shows speckles light scattering pattern images for undistorted and distorted droplets diameters of approximately 7 ... 16 μm. These latter results indicate the locally changes in droplet velocity and droplet flow direction that produce the increasingly complex scattering data. The morphological transition coincides with the dominant changes in flow conditions and are currently under investigation with the hope of elucidating the cause of the dominant scattering features.

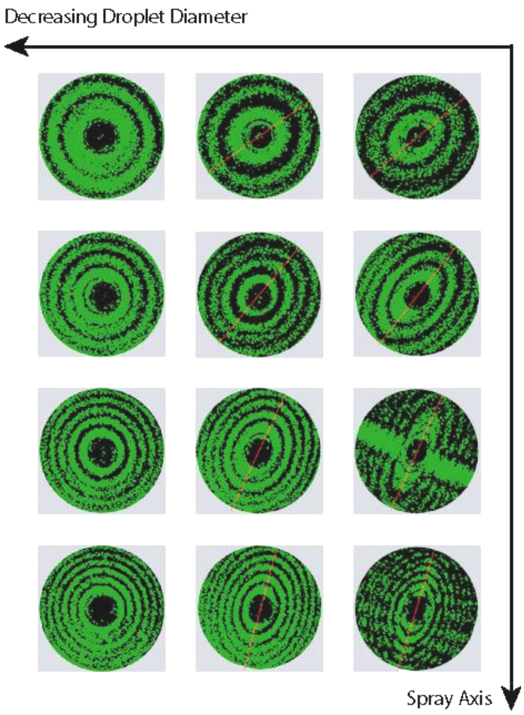

Fig. 3 Speckles scattering patterns from individual droplets

5. Macroscopic spray characterization

Determination of macroscopic (geometrical) spray characteristics as cone angle, spray tip penetration, air entrained by the spray, etc. mainly a large range of illumination devices, from Xe lamps to continuous or pulsed lasers are used for shadowgraphs of the sprays. The localization 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, or to the circumstances that the edge droplets and the number density are often too small to be detected. 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 or inaccurate.
The purpose of this study is to make use of the described novel laser speckles based imaging technique to detect spray boundaries in DI Diesel sprays. The system must work with images

from different facilities, which provide different experimental approaches to actual engine behavior; high pressure-high temperature cells and running engines.
The experimental technique proposed in this paper has been successfully applied to spray studies.

5.1. Diesel speckles spray image restoration

Most of the common algorithms can be considered good enough for all kinds of images and especially for speckles images. Prior to the application of the algorithm, some degradation effects in the speckles image system were evaluated and corrected with standard digital image-processing algorithms applied in sequential order:

1. Transverse magnification, different at the horizontal and vertical directions owing to the CCD structure, is corrected with a spatial scaling of the images.
2. Thermal noise and spatial patterns due to CCD characteristics are corrected by applying a neighborhood averaging
3. Finally, a mean of background images is subtracted to correct partially the no uniform background level, and a given fixed and arbitrary value is added to avoid negative values in the images. With this procedure the maximum that corresponds to the background distribution in the histograms will be near this given value, which facilitates detection of this maximum.

5.2. Injection – Combustion images in a high pressure – high temperature cell

The preprocessed Diesel spray speckles images contain only two regions: that occupied by the Diesel spray and that corresponding to the background. The histogram of an image may be considered an estimation of the brightness probability density function. This function is the weighted sum of two unmoral probability density functions, one for the Diesel spray and one for the background.
The proposed speckle imaging technique together with the algorithm are shown in Figure 4, in which the boundary detected is overlaid with an equalized, distortion corrected image and compared with the boundary detected by e.g. shadowgraph image.

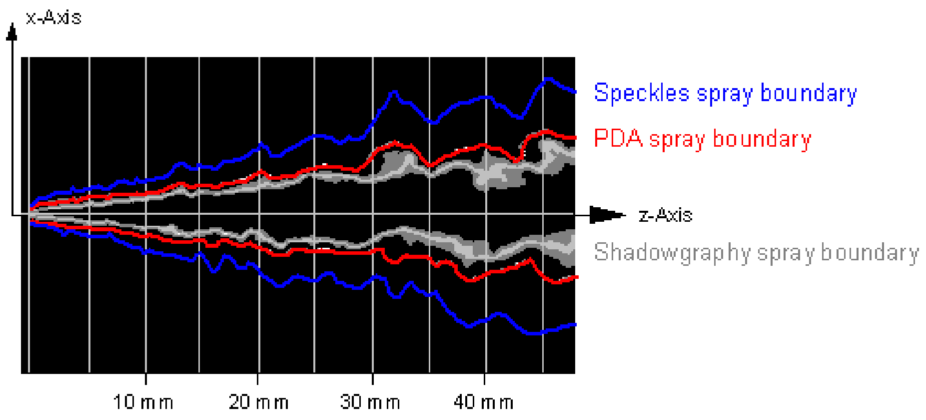

Fig. 4 Visualization of the macroscopic behavior of a Diesel spray

6. Conclusions

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 two dimensionally, simultaneous 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 ma ultimately provide a route to the rapid characterization to sprays In modern Internal combustion engines.

7. Acknowledgements

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