# DETECTION OF NONSPHERICAL DROPLETS OF INJECTION SPRAYS IN A HIGH PRESSURE – HIGH TEMPERATURE CELL

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## Abstract

Experimental results are provided to illustrate the complex speckle-scattering behavior of nonsperical droplets at different locations within the spray. Furthermore, a correlation of the data between the velocity field and the shape of the droplets lead to improved knowledge on the influence of flow characteristics and droplet size.

# **Introduction and Background**

A novel laser speckles based imaging technique for droplet size visualization and measurements of injection sprays in

<u>DI diesel engines</u> and in a high temperature, high pressure combustion cell was developed 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 system in DI diesel engines

<u>High Pressure – High Temperature Combustion Cell</u> 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.

# Instrumentation

# 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.

## Droplet detection system

The droplet detection system was designed in order to visualize droplets in the range of  $2.0 \,\mu\text{m}$  to  $100 \,\mu\text{m}$ . 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  $\mu$ m. The speckle size can be varied as mentioned in [1], by changing the aperture respectively the fiber diameter.



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

# Experimental

# 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  $2^{nd}$  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.

## 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 of the droplets as shown in Figure 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  $\mu$ m x 338  $\mu$ m) lies 1mm above the spray axis. Measurement have been performed at different location from the spray orifice. Figure 2 shows a typical result of the D10 diameter distribution and the appropriate droplet size classification within the observed diesel spray area.



FIGURE 2 Droplet D10 diameter (left) and droplet size classification (right)

The displacement of the double exposed reflected/refracted droplet images have been analyzed in small segments (interrogation spots) with correlation methods. The analyzed droplet displacement combined with the magnification factor of the optical setup, leads to the droplet movement within the fuel spray, whereas the displacement vector, divided by the given time interval, yields an in-plane velocity of the droplets. Analysis of all interrogation spots yields the instantaneous two-dimensional velocity field in the observation plan as shown in Figure 3.



FIGURE 3 Radial velocity (left) and velocity fields (right)

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 [2] and Griffiths et al., [3] 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.

## **Spatial Light Scattering**

The spatial distribution of light scattered by a particle, also in certain texts referred to as the twodimensional 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.

## 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.

# 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  $5^{\circ}$  and  $25^{\circ}$  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.



Figure 4 Schematic representation of droplet shape detection

# 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 5 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 scattering 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 5.

Figure 5 shows speckles light scattering pattern images for undistorted and distorted droplets diameters of approximately 7 ... 12  $\mu$ m. Adjacent to each scattering pattern is the corresponding velocity field observation. 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.



Figure 5 Velocity field (left) and corresponding detected scattering patterns (right)

# **Quantifying Droplet Deformation**

As a comparative measure, the distances between of the scattering maxima and minima on the pattern in the x and y directions were determined by a computer-based Gaussian edge detection algorithm. The threshold value for this algorithm can be set manually or left to be determined automatically from the background intensity. Because the background intensity is different for each pattern, the automatic threshold function was employed. I addition, the graininess of the background can make the algorithm detect erroneous maxima and minima in the background.

Up to now droplet distortion produced in a spray has been computed through an analytical solution of the Navier-Stokes equation and leads to a means of correlating observed droplet deformation to parameters such as droplet diameter viscosity, surface tension, and density. A high Reynolds number empirical approximation to the pressure external to the droplet is envisaged.

# Discussion

The presented experimental data illustrate the complex spatial speckles scattering behavior of distorted droplets. The reproducibility of experimental data makes them a valuable resource in the testing of theoretical models. Such models may ultimately provide the rapid characterization and identification of complex droplet shapes, and thus in turn could lead to advances in simulation of sprays.

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