

Optical Characterization of a Diesel Spray at High Temperature and Pressure

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Abstract

The analysis of diesel sprays in engine-like conditions is of fundamental importance for the study and development of diesel engines.

Laser diffraction techniques were used in this work to study droplet size distribution of a diesel spray injected into a constant-volume combustion vessel with line-of-sight optical access. The experiments were conducted using a common rail injector electronically controlled to inject after the combustion of a stoichiometric air-methane mixture. This allowed to reach temperature of around 1000 K and pressure of more than 10 bar.

In the first stage of the work back-light technique was employed to measure spray characteristics such as penetration and cone angle. The liquid phase behavior was highlighted by means of a high-speed digital camera for different values of injection duration and pressure. In the second phase particle size distribution and pertinent attributes of the distribution were measured on the spray axis at 10 mm from the injector orifice.

The obtained results were finally discussed putting in evidence the main sources of disturbance encountered during the measurements and illustrating their effects on the measurement accuracy.

1. Introduction

Diesel sprays have been extensively studied in recent years due to their role in achieving an efficient and clean combustion.

Even though the effect of gas density downstream of the injector has been widely investigated, experiments have been carried out mainly at room temperature where fuel vaporization is not present. Only a few papers have focused on the influence of temperature on spray penetration and cone angle, both at constant and varying air density. Anyway, to the knowledge of the authors, particle size distribution has not been investigated extensively due to problems arising when optical techniques are used under engine-like conditions.

In order to characterize a diesel spray at high temperature and pressure, a special test rig was built which allowed to achieve engine-like conditions through the combustion of a gas mixture. Pressure and temperature profiles were controlled via suitable transducers placed inside the test vessel. The injection was performed when the desired pressure and temperature conditions were reached. High-speed camera images and laser diffraction patterns were acquired to study the temporal evolution of the spray inside the vessel.

2. Background

2.1 Spray tip penetration and cone angle

The role of injection system characteristics has been widely studied [1-6] considering the effect of ambient density in pressurized vessels at room temperature. Empirical and semi-empirical correlations between macroscopic and microscopic spray features and injection parameters were soon available from the first studies and are still object of intense research.

Naber and Siebers [7] investigated spray development in the 300-450 K and 600-1400 K temperature ranges using measurement systems based on the Schlieren effect to represent also the vapor phase of the spray. They found out that the spray angle increases with the ratio between air and fuel density and established an experimental correlation between the mentioned values for both cases of vaporizing (600-1400 K) and non-vaporizing spray (300-450 K). When spray vaporization is present spray cone angles assume smaller values with differences sometimes close to 30%. This fact can be attributed to vaporization of small droplets at the spray periphery and also to the cooling of the air around the spray boundaries. The effect of this phenomenon is a reduced air entrainment rate and the variation of the injection pressure has a small influence on this, as it did at room temperature. Spray tip penetration is on the contrary reduced from an increase in air density because much of the spray energy is transferred to the surrounding air. When vaporization occurs, spray penetration is even smaller probably due to the cooling of the surrounding gases which increase their density and slow the penetration of the spray droplets. Quantitatively differences of about 30% can be found at low densities with respect to the absence of vaporization. Hence an increase in temperature causes the penetration to be greater, as lower densities are achieved with higher temperature. This effect is more pronounced for low density values, but is still important at higher densities when the injection pressure is elevated; whilst the penetration is lower when temperature is increased at a constant density value [8].

2.2 Spray droplet size

Studies about drop size distribution have grown since the advent of optical instruments based mainly on laser diffraction and phase Doppler anemometry [9, 10, 11]. Results are obtained from processing the diffraction pattern produced by a drop distribution in the case of laser diffraction systems, and from the analysis of the refractive scattered light from a small volume in the spray in the case of phase Doppler anemometers. All the measured spray characteristic quantities are treated statistically due to the transient nature of the spray which causes drop size distribution parameters to continuously vary in time and space. Moreover breakup and coalescence phenomena occurring during the injection alter the measured distributions making it possible to determine only a mean diameter. *Coil and Farrell* showed [12] that diffraction-based technique has the advantage of giving detailed local spatial information which demonstrate very well the transience of the spray with respect to time ranging data or qualitative data from the whole spray. In this sense laser diffraction is preferred to other optical techniques, but much attention must be given to the interpretation of the results in dense sprays where the obtained drop distribution may be misleading and inaccurate [9]. Several studies have been conducted with the aim of analyzing effects that the injection parameters may have on the SMD (Sauter Mean Diameter) which is usually the preferred quantity used to describe drop size distribution in a diesel spray. It was generally and almost obviously ascertained that an increase in the injection pressure causes a reduction of SMD and that a decrease in the injector nozzle diameter has a quite similar effect. On the contrary, the SMD evolution with time does not present a noticeable variation and an increased injected quantity produces only a slight increase of the particles diameter.

In [13] the droplet size distribution is analyzed using the PDA (Phase Doppler Anemometry) technique which allows also the simultaneous determination of the droplets velocity field. However measurements were not possible closer than 10 mm from the injector tip, since the spray optical density is too high in the vicinity of the injector and prevents further investigations based on this technique. In that paper, the air density was changed from 1 to 30 kg/m³ and a reduced SMD was observed for decreasing density, suggesting a direct proportionality of the particle diameter to the density value ρ_a , and precisely to $\rho_a^{0.4}$. The most likely explanation is that an increased resistance due to a higher density causes the spray to slow and the breakup is reduced as a consequence of a lower droplet velocity. A more recent work [4] reported the following experimental correlation between the SMD and some of the injection characteristics:

$$\text{SMD} \propto d^{0.3} * P_{\text{in}}^{-0.1} * \rho_a^{0.1} * t^{0.2} \quad (1)$$

where d is the injector orifice diameter, P_{in} is the injection pressure and t is the particle time of residence in the injection environment after the injection itself. The SMD evolution after the spray injection is therefore influenced by the time during which the fuel droplet is in effective contact with hot ambient gas. A numerical calculation taking into account density variation with temperature [14] confirmed this relationship, showing the dependence of the SMD on the time elapsed from injection, strictly related to the vaporization of the smaller particles which cause a decrease in the droplets mean radius.

3. Experimental setup

3.1 Fuel injection system

The spray analyzed in this work was generated by an electronically controlled common rail injection system. The injection was triggered by a TTL signal which allowed the synchronization with the detonation of an air-methane mixture.

The test injector used in the experiments has a mini-sac nozzle with one orifice. The hole has diameter of 0.275 mm and length of 1 mm, which gives l/d ratio of 3.63.

The injector flow rate was measured using a Bosch-type rate tube at the desired test conditions (injection pressure and solenoid energizing time) and measuring the injected quantity of fuel.

Injection pressure was measured in the rail by means of a 4067 Kistler pressure transducer (max. pressure: 2000 bar, sensitivity: 5 mV/bar, linearity: ± 0.5 %). The fuel pump was powered by an electric motor running at 1000 rpm.

The injections occurred into a constant volume combustion vessel (figure 1) to simulate engine conditions. The high temperature and pressure condition was achieved through the combustion of a methane-air mixture. The mixture was created inside the vessel by accurately measuring the partial pressures of both gases at ambient conditions. Partial pressures were chosen so that a temperature of approximately 1000 K could be achieved at the end of the gas combustion, at a pressure not greater than 20 bar. The chosen methane partial pressure which guaranteed these conditions was 0.3 bar, corresponding to an air partial pressure of 1.8 bar. A digital Delta Ohm HD9220 (max pressure: 10 bar, accuracy: ± 0.8 %) manometer was employed to check the methane pressure and for the absolute pressure determination inside the vessel after the introduction of the air. Both gases were let in through two valves positioned on the top of the chamber (figure 1).

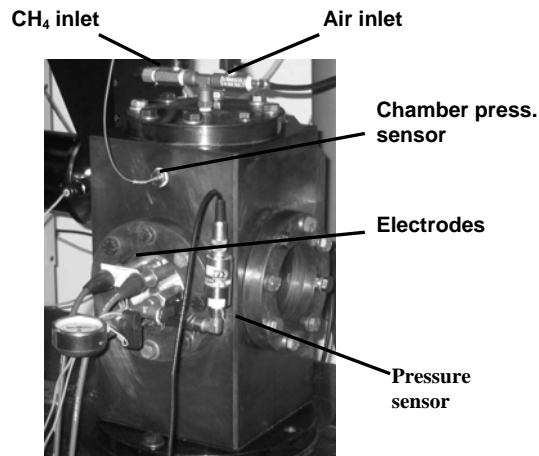


Figure 1. Constant volume combustion vessel used for the experiments.

To measure test conditions inside the chamber, the vessel was equipped with pressure and temperature sensors. The main issue that drives the problem in this regard is the dynamic response of the sensors, that have to follow in an accurate way the pressure and temperature profiles of the air-methane combustion phenomenon.

The pressure achieved after the air-methane combustion was monitored using an AVL GU12P pressure sensor (max. pressure: 200 bar, sensitivity: 16.54 pC/bar, linearity: $\pm 0.06\%$).

The choice of the temperature sensor was accomplished taking into account the dynamics of the phenomenon to be monitored. The temperature rising inside the chamber can be divided in two different parts. In the first one there is a quick increasing of temperature, which is of about 1000 K, due to the mixture combustion, that occurs in about 250 ms; in the second part there is a temperature decreasing, due to the cooling of the combusted products, that occurs in a few seconds (see expected temperature profile in figure 3 and 4). The sensor dynamic response is established by modeling the thermocouple as a first order system, assuming to use bare thermocouples. The temperature profile inside the chamber is described by two parts: a step function from 300 K to 1200 K in the time from 0 s to 250 ms and an exponential decay function from 250 ms on (equation (2)):

$$T(t)=T_0\exp(-t/\tau) \quad (\text{for } t > 250 \text{ ms}) \quad (2)$$

where $T_0=1381.99$ K and $\tau = 1.77$ s for this phenomenon.

The thermocouple measuring junction is schemed as an homogeneous material sphere of external surface A , mass m and specific heat capacity c , in a fluid with a convective heat coefficient h . Hence the calculated response function is:

$$T(t) = 1200 - 907 \exp(-t/\beta_1) \quad (\text{for } 0 < t \leq 250 \text{ ms}) \quad (3)$$

$$T(t) = C \exp(-t/\beta_2) + T_0 \frac{\tau}{\tau - \beta_2} \exp(-t/\tau) \quad (\text{for } t > 250 \text{ ms}) \quad (4)$$

where $\beta = \frac{mc}{hA}$ is the time-constant of the sensor and C is a constant determined by the initial conditions.

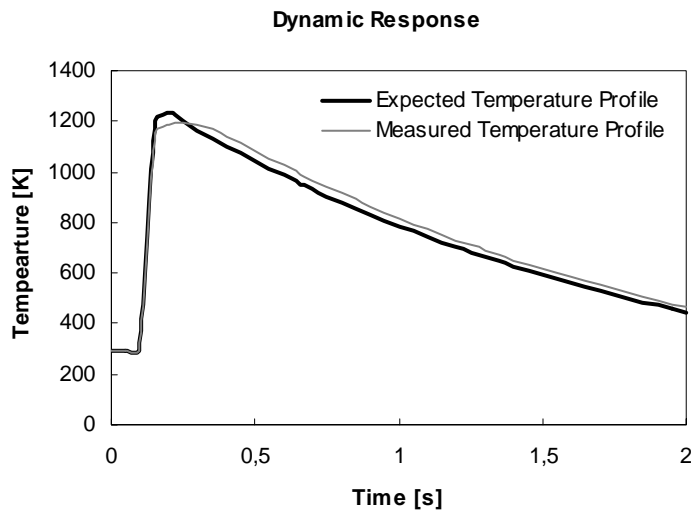


Figure 2. Temperature profile measured by a 50 μm thermocouple

Using the model described by the functions in equations (3) and (4), it was possible to verify the sensor dynamic response. In particular the influence of the junction material (considering K-type and S-type thermocouples) and dimensions was verified, considering a diameter between 1 mm and 25 μm . The theoretical model shows that, as it may be expected, the most influencing parameter for the dynamic response of the sensor is the junction diameter. In figure 2, the dynamic response of a thermocouple with a junction diameter of 50 μm is shown and it can be seen that the sensor is capable to accurately follow the temperature variation, thanks to its low thermal inertia.

Taking into account these considerations, a pair of K-type thermocouples with diameter of 50 μm were placed into one side of the vessel, opposite the injector side, at same height.

Detonation of the air-methane mixture was achieved by a spark generated through a special circuit with a relay which can be triggered. In this way it is possible to retard the injection of the wanted time delay with respect to the beginning of the combustion, so that injection occurs at the desired pressure and temperature which are controlled by the sensors.

3.2 Spray visualization system

Figure 3 shows the experimental arrangement used to keep track of the spray macroscopic features via back-lighting techniques.

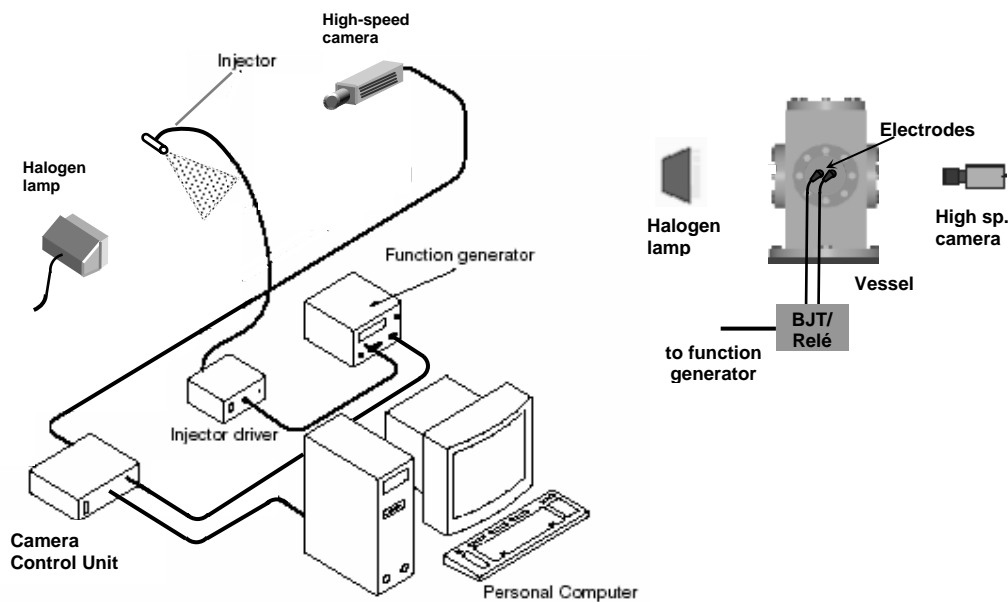


Figure 3. Experimental apparatus for spray visualization.

For a fast imaging of the spray, a high-speed (max frame rate: 10 kHz) digital camera (Kodak Motion Corder Analyzer) was used, which has 658x496 active pixels. Resolution is obviously related to the frame rate used; in this case images were sampled at the maximum possible frequency, meaning that the images were time spaced of 0.1 ms with a resolution of 128x64 pixels. The scene was illuminated by an halogen lamp placed on the opposite side with respect to the high speed camera (see figure 5). The starting of the image capturing was synchronized with the start of the injector driver current. Due to the needle opening delay time, the effective appearance of the spray on the images was delayed usually by four frames (0.4 ms).

3.3 Droplet size measurement

Figure 4 shows the measurement setup used for the droplet size measurement where a Malvern Spraytec RTS 5000 was employed for the determination of the PSD (particle size distribution) throughout the spray.

To determine drop size distribution the instrument detects and processes the diffraction pattern that is generated when droplets are illuminated by a coherent light beam. The Malvern Spraytec used in this work is composed by a laser source (Class IIIb He Ne 5mW Max CW diode laser), a diffracted light detector and a personal computer for the instrument control, data acquisition and processing. A special software module (“Flash mode”, [8]) allowed a maximum sampling frequency of 2500 Hz (time space between two subsequent samples: 400 μs) and the synchronization through the detection of a signal from an external trigger input to the system control card.

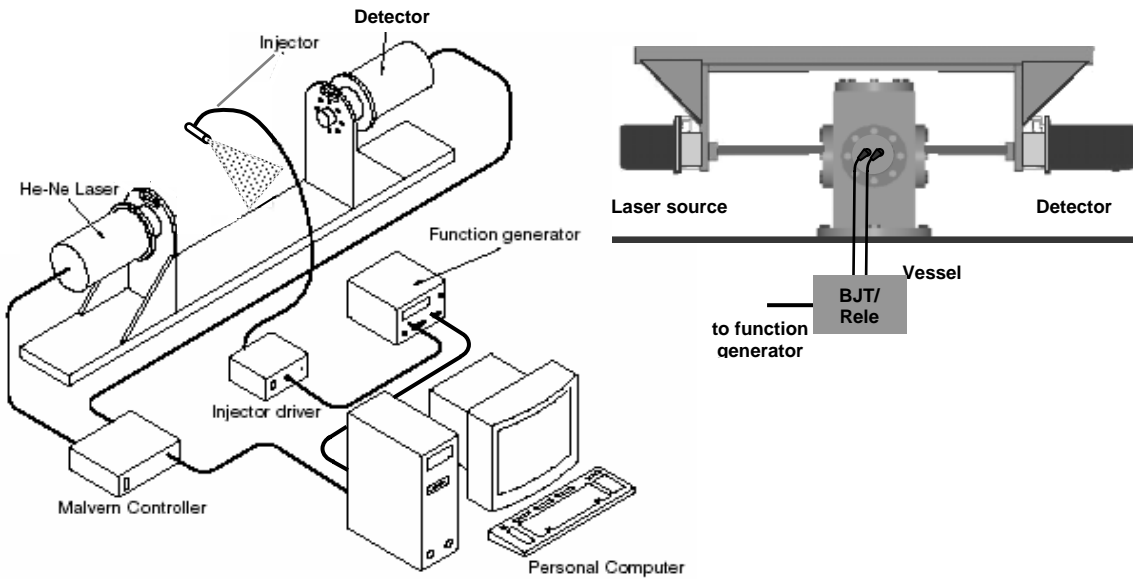


Figure 4. Experimental apparatus for droplet size measurement

The Malvern instrument was used to measure the Sauter Mean Diameter (SMD), given by:

$$SMD = \frac{\sum nD^3}{\sum nD^2} \quad (5)$$

where D is the droplet diameter, and represents an equivalent drop distribution which presents the same total volume and total surface of all particles. It is often indicated as D[3,2].

The instrument stated accuracy is evaluated using the RS-3 reference standard reticle [8], an optical glass plate with a photographically deposited pattern of 10,000 particles with known size distributions in terms of mean diameters and relative uncertainties. Based on this reference, the overall uncertainty is not greater than $\pm 3\%$ and is determined from the comparison of the computed and reference particle size distribution.

The problem of multiple scattering was addressed by introducing a patented correction algorithm [15] which accounts for the probability that n scattering events may occur in an optically thick spray. The correction factor is a function of the light transmission, which is inversely proportional to the optical depth of the particle field, and of the particle size distribution itself. The claimed uncertainty is of $\pm 1\%$ of the value, down to transmission of 2%.

4. Results and discussion

4.1 Spray tip penetration and cone angle

The photographic characterization of the spray was accomplished in the test conditions of injection time and pressure reported in table 1, for two different temperature values ($T_1=1085$ K, $T_2=623$ K), corresponding respectively to 12 bar and 6 bar pressures and at ambient temperature and pressure ($T = 300$ K and $P = 1$ bar) (see Figures 5-7).

At 300 ms and 600 ms after the mixture denotation the measured temperature values were therefore 1085 ± 78 K and 623 ± 34 K respectively. The corresponding pressure values are 12 ± 1 bar and 6 ± 1 bar respectively.

Table 1. Test conditions for the photographic analysis.

Test conditions	inj. pressure: 600 bar energ. time: 400 μ s	inj. pressure: 400 bar energ. time: 600 μ s	inj. pressure: 600 bar energ. time: 600 μ s
Injected quantities	$11.08\pm 1.35\%$ mm ³	$11.56\pm 1.49\%$ mm ³	$18.13\pm 1.20\%$ mm ³

The goal of the photographic characterization was to support the laser diffraction measurements, through description of the spray spatial and temporal evolution. The number and locations of the laser spots, key to a meaningful investigation of the spray, were derived from this kind of information.

T=300 K, p=1 bar



T=623 K, p=6 bar



T=1085 K, p=12 bar



Figure 5. Spray evolution inside the vessel (inj. pressure: 600 bar, energ. time: 600 μ s).

T=300 K, p=1 bar



T=623 K, p=6 bar



T=1085 K, p=12 bar



Figure 6. Spray evolution inside the vessel (inj. pressure = 400 bar, energ. time = 600 μ s).

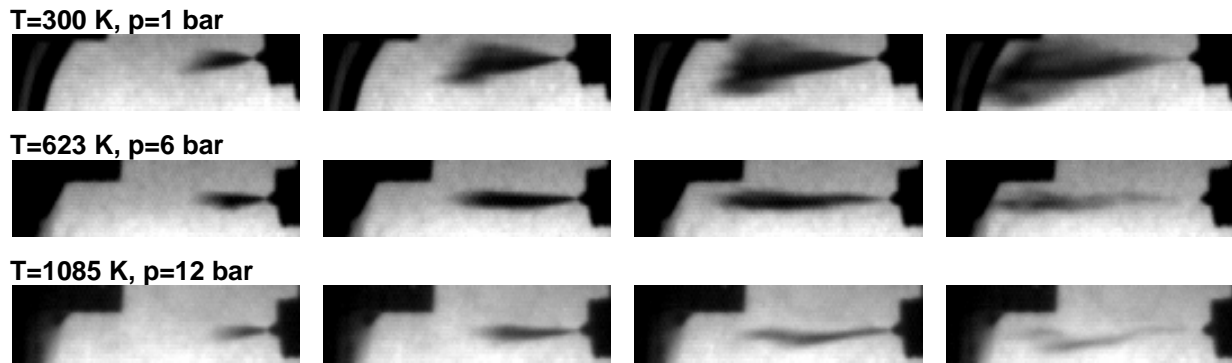


Figure 7. Spray evolution inside the vessel (inj. pressure = 600 bar, energ. time = 400 μ s).

4.2 Droplet size

In order to outline a measurement procedure taking into considerations the measurement problems existing when employing laser diffraction at high temperature condition, initially one test condition was considered, corresponding to a temperature of 623 K (pressure = 6 bar). The measured PSD (particle size distribution) was compared to that determined at ambient temperature and pressure, at 10 mm from the injector tip (see Figure 8), for 400 bar injection pressure and 600 μ s energizing time.

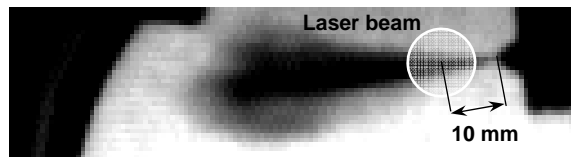


Figure 8. Laser spot position.

The PSD was firstly determined at ambient temperature and pressure, in order to compare the droplet mean diameters obtained in the different conditions and analyze major deviations. Since the realization of the high temperature environment requires the injector to operate in “single-shot” mode, measurements at ambient temperature were made under the same condition. This way of carrying out the experiments facilitated the diffraction measurements, as a repeated number of injections presents one major drawback. If the injector sprays intermittently at a defined frequency, close to the real operation, the spray area is soon surrounded by very small (a few microns) droplets which shift the PSD down to lower values. It is not very useful in this case to measure the background (obtained measuring without injecting) since the number of the residual droplets decays with time and increase with the injections number. Evidence of that was achieved by comparing PSDs after a variable number of injections obtaining SMD values which sometimes differed of more than 30%. Based on these observations, measurements were carried out waiting between one injection and the following until an acceptable and stable background was achieved. This increased the total acquisition time, but assured a higher measurement accuracy.

For comparison between data taken at ambient and high temperature it was decided to measure on the spray 600 μ s after the start of the injection which represents the time frame where the spray is completely on the laser line-of-sight, as it can be seen on the left in figure 9. Acquisitions were repeated until a total of 20 measurement data were gathered on the spray in order to evaluate the measurement repeatability in the mentioned condition. The calculated SMD value was 12.2 ± 1.8 μ m. Causes for scattering of the measured values can be attributed mainly to the nature of the spray itself, to injector defects and to the existence of multiple scattering. Break-up and coalescence effects co-exist in the spray due to droplets interaction between themselves and with the surrounding air and are influenced by cavitations phenomena inside the injector nozzle and the

injection conditions, mainly injection pressure. The latter is established by a Common Rail System and is not perfectly stable with time, presenting oscillations up to 5% of the desired value.

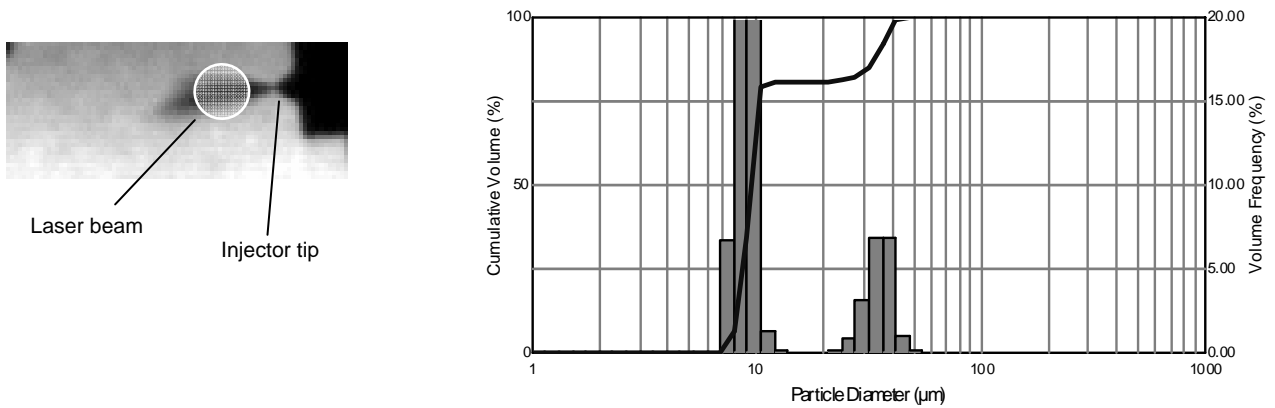


Figure 9. Typical Particle Size Distribution (right) at 10 mm from the injector tip (left) (inj. pressure = 400 bar, energ. time = 600 μs).

As a result, the particle distribution can only be described statistically and represented by mean values like the SMD, which are not perfectly repeatable as previously shown. Besides, the injector may spray out-of-axis, partially out of the area illuminated by the laser beam.

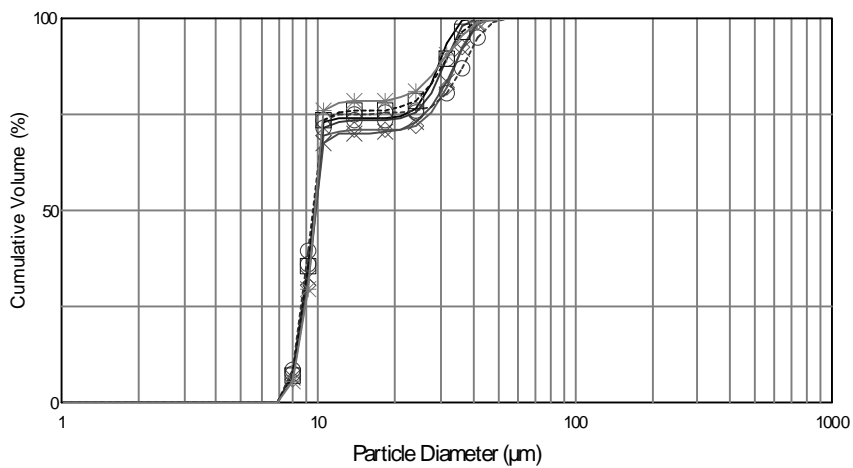


Figure 10. Particle Size Distributions obtained for SMD values between 10.8 μm and 11.4 μm.

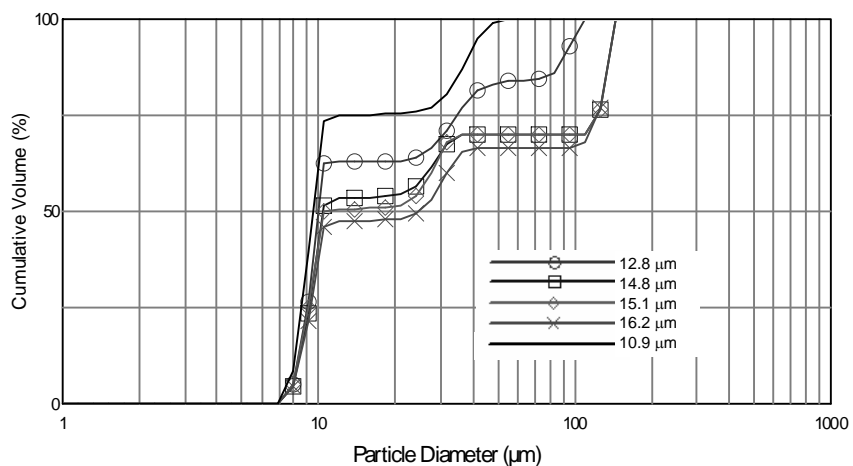


Figure 11. Particle Size Distributions obtained for the indicated SMD values.

It was also noticed that, while the majority of the PSDs are in the shape reported on figure 10, a few measurements deviate from the expected behavior showing a cumulative volume distributed as reported in figure 11. Analyzing these droplets size data it was found out that the SMD increase is due to a very small percentage (0.01 to 0.03 %) of bigger particles, usually with mean diameters greater than 100 μm . These particles are most probably part of the spray front that may be partly measured when the N.O.D.T. (needle opening delay time) is slightly lower or simply because the bigger particles move faster out of the measurement area due to a higher inertia with respect to the smaller (and lighter) particles. A few particles of this type shift the SMD to higher values and have of course a marked influence on the cumulative volume.

As regards the multiple scattering effect, a comparison between the corrected and uncorrected SMD values may be made in order to evaluate the uncertainty due to this phenomenon, according to the algorithm included in the system software. The correction is made based on the transmission value and size distribution and therefore, when a slight percentage of bigger particles exist, the correction is more marked. Without data modification which accounts for the multiple scattering, the measured SMD is $11.0 \pm 1.1 \mu\text{m}$. While the uncertainty is slightly lower, the mean value differ of around 9% with respect to the corrected estimate (12.2 μm). The uncertainty evaluated on the correction algorithm itself (1%) must also be included in the overall estimate.

It can be noticed that the absolute difference between the mean values (1.2 μm) is smaller than the measurement repeatability meaning that the “errors” on repeated SMD measurements are in certain cases higher than the uncertainty due to multiple scattering. This is most often the case when particles with diameters bigger than 100 μm are not estimated in the measuring area.

When considering injections at high temperature, the task of measuring by the laser diffraction technique gets more complicated. The first problem consists in the quartz windows contamination due to water vapor deposition after the air-methane combustion. Windows opacity lowers the transmission and causes a misleading size distribution. Due to the windows thickness and to the quartz thermal inertia it is not possible to raise their temperature from outside the chamber. A way to solve this problem is to raise the windows temperature by heating them through a number of mixture combustions sufficient to obtain an acceptable and stable background. The combustion have the effect of heating the vessel walls and therefore the windows temperature. Examples of “good” data obtained from the experiments are reported on figure 12.

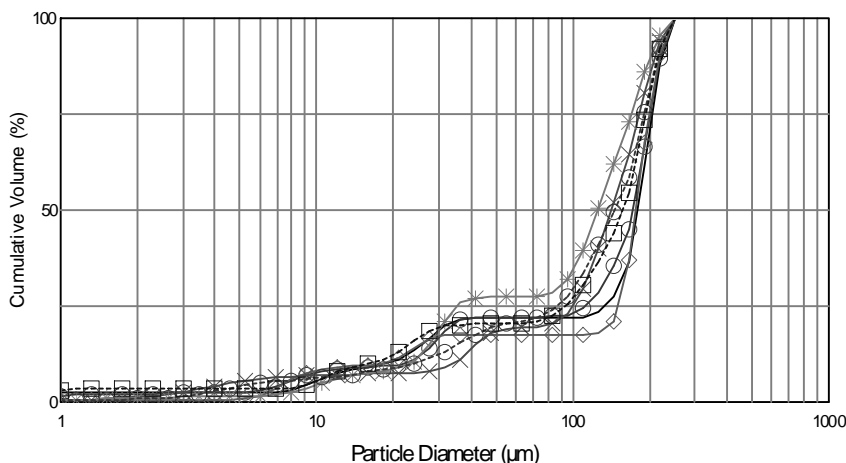


Figure 12. Particle Size Distributions obtained after the mixture ignition.

Measurements with transmission lower than 10% were rejected as well as those presenting ring signal saturation. The remaining droplets distributions are very similar and different consistently from the PSDs obtained at ambient temperature (figure 9). The average PSD from a series of 10 valid measurements is reported on figure 13 and should be affected by a lower noise level. It can be

seen that the volume content is dramatically shifted towards higher diameters, revealing that a number of bigger particles of mean diameter greater than 200 μm appear with respect to previous data. The mean SMD is increased, being this time 27.5 μm . Anyway, the uncertainty on its measurement is neatly higher due to the existence of disturbances during the tests. The standard deviation of the data is 5.1 μm , which is around 18% of the mean value. The SMD is much probably shifted towards lower values due to small vapor particles. Values related to the cumulative volume presented instead a lower scattering, especially diameters pertinent to the equivalent distribution which contain 90% of the total volume (D_{90}).

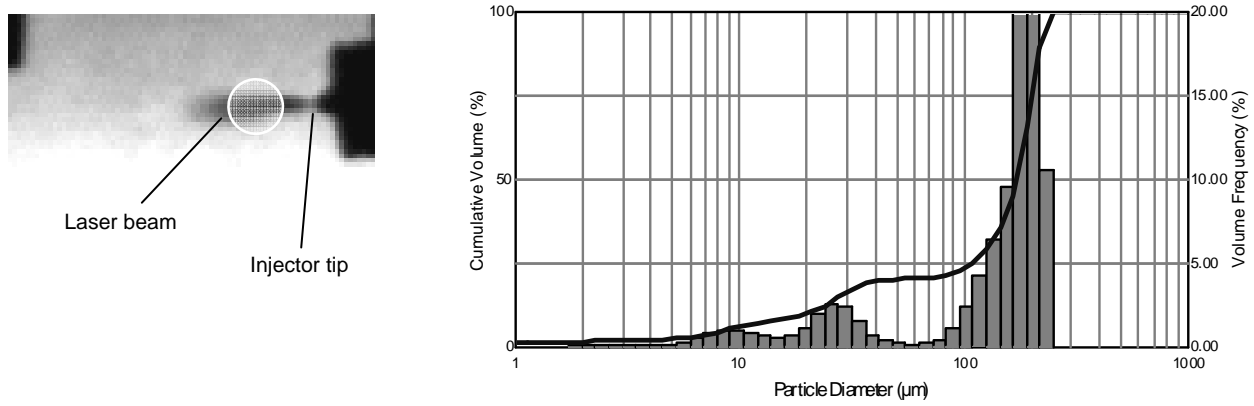


Figure 13. Average Particle Size Distributions obtained from data reported on figure 12.

The measured D_{90} was $218.3 \pm 3.6 \mu\text{m}$ and the D_{50} which is relative to the 50% of the total volume, was $165.7 \pm 13.1 \mu\text{m}$. Considered that the injector orifice diameter was 275 μm , the D_{90} was about 80% of it. Comparison between characteristic diameters describing the particle size distributions at ambient and high ($T = 623 \text{ K}$) temperature is reported on table 2.

Table 2. Comparison between characteristic diameters at ambient and high temperature.

Diameter	SMD [μm]	D[4,3] [μm]	D_{10} [μm]	D_{50} [μm]	D_{90} [μm]
T=300 K	11.0 ± 1.1	15.3 ± 1.9	8.0 ± 0.1	9.6 ± 0.1	34.2 ± 1.9
T= 623.64 K	$27,5 \pm 5.1$	144.2 ± 9.6	23.9 ± 6.1	165.7 ± 13.1	218.3 ± 3.6

All the measured diameters are lower at ambient temperature, increasing noticeably when the temperature is practically doubled. The D[4,3] is called De Brouckere Mean Diameter and is given by:

$$D[4,3] = \frac{\sum nD^4}{\sum nD^3} \quad (7)$$

which corresponds to the center of gravity of the volume (mass, if the density is constant) distribution; the SMD had the same meaning referred to the surface area distribution. D[4,3] is the primary value calculated by laser diffraction and its variation in the different temperature conditions examined is stronger. At the same time, it is less affected by an eventual high number of small particles due to combustion and therefore much reliable for comparison purposes. It is much increased at 623 K, suggesting that the centers of gravity of the volume distribution is shifted towards higher diameters. This would mean that the smallest particles vaporized, and would be in accordance with the observations outlined for spray penetration and cone angle. Penetration is reduced proportionally to the temperature increase, and this can be attributed to vaporization at the

spray tip. Spray cone angle is also reduced, probably due, as already commented, to vaporization of small droplets belonging to the spray periphery.

5. Conclusions

In this paper the spray produced by a common rail single-hole injector has been analyzed under different conditions of pressure and temperature of the injection chamber environment and the results of this investigation have been reported.

Back-lighting technique was employed to study spray development under a series of fixed temperature and pressure, for two different values of the injection pressure and injected quantity. This allowed to visualize the evolution of the liquid phase, studying its penetration and cone angle, and gave useful spatial information for locating the laser beam for droplet size measurement.

Droplet size data obtained at high temperature (623 K) and pressure (6 bar) were compared to those acquired at ambient conditions. All the results were obtained from single-shot injections, thus limiting the noise due to the existence of clouds of small droplets which remains in the measurement area from previous injections. At high temperature measurement problems of different nature were to be handled: quartz window contamination, which was acceptably reduced by heating the internal vessel environment, low transmission due to the presence of combustion products, ring saturation occurring due to partial fuel ignition which may sometimes occur. For these reasons, data with transmission lower than 10% and presenting signal saturation were rejected.

PSDs obtained at high temperature were substantially different from those measured in ambient condition. All the characteristic diameters increased: while the SMD has only doubled, from around 12 to 24 microns, the quantities relative to the particles cumulative volume have considerably grown. This suggested the number of bigger particles increases at high temperature, probably due to vaporization of smaller droplets, especially at the spray periphery.

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