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Determination of the optical depth of a DI diesel spray

Francisco Payri, Jose Vicente Pastor, Raul Payri (rpayri@mot.upv.es) and Julien Manin
[1] CMT Motores Termicos, Universidad Politecnica de Valencia, SPAIN

Abstract

The optical depth is responsible of limiting the optical diagnostic using visible wavelength in the sprays. This paper proposes to measure the optical depth directly in a real Diesel spray through line-of-sight laser extinction measurements. This easily reproducible method which does not require expensive or complex optical techniques is detailed and the measurement procedure is presented in this paper. As diesel sprays are mostly optically thick, the measurements in the denser region are not reliable and a fuel concentration model has been used to derive the results to the entire spray. This work provides values of SMD at different distance from the nozzle tip depending on the specific parameters like injection pressure or discharge density. The values extracted from a combined experimental/computational approach have been compared to PDPA measurements under the same testing conditions. The results have shown that the maximum optical depth was higher than 10 and that an increase of the injection pressure led to higher τ values. The SMD values appeared to be below the results measured by the PDPA and the droplet diameter showed to be the main responsible of the optical depth of the jet under the tested conditions.

Keywords: Diesel, Light extinction, Optical depth, SMD, Sprays.

1. Introduction

he impressive development of Diesel engines in the last decades, making them cleaner and more efficient, has been largely a consequence of the improvement of the injection systems performance and flexibility, and the implementation of new combustion strategies (LTC, MK, PCCI among others) [[1]-[3]] that are mainly based on the use of advanced injection strategies and high EGR rates. Thus, DI Diesel spray properties have been deeply investigated and new technologies have been developed to increase the engine efficiency by providing injected spray with higher air entrainment and so better mixing processes by reducing orifice size, increasing injection pressure and redesigning nozzle geometry that finally increase combustion efficiency and reduce pollutant emissions [[4]-[6]].

In the different institutions that perform research on Diesel engines, a lot of different techniques are used to analyze the spray either macroscopically or microscopically, from basic parameters like tip penetration or spray cone angle obtained through macro-spray visualization [[3]] to the really complex X-Ray absorption techniques [[8]] to determine the fuel mass distribution or ballistic imaging [[9]] to see the micro-structures of the spray with a short time-gated imaging method. Depending on the aim of the study done on the injected spray, these different techniques can be applied with some restrictions. Ballistic imaging and X-Ray absorption require specific and expensive installations, but many other laser techniques using visible light (Mie scattering imaging, Phase Doppler Anemometry [[10]], Laser Induced Fluorescence [[11]] among others) are widely applied to Diesel spray research.

The problem using visible light in a spray is that multiple scattering strongly affects the propagation of the electromagnetic wave through such a turbid media [[12]]. Several researchers applied the LIF/Mie technique in order to get an SMD distribution map of the spray, but the multiple scattering affects the propagation of light differently for elastic scattering (Mie) and inelastic scattering (Fluorescence, LIF) and makes the LIF/Mie ratio only reliable for concentration situations in a limited range [[13]]. To partly solve this problem, some correction techniques are available in the literature [[14], [15]]. Pastor et al. [[16]] also developed a correction technique to apply the LIF/Mie ratio to get maps of SMD; this method called the Linear Sizing Technique (LST) corrects both LIF and Mie signals on the original images.

Limitations of the techniques presented that claim to reduce or avoid the effect of scattering matters are not always considered in the literature. The efficiency of these correction methods can vary depending on the different parameters like injection pressure, nozzle geometric design, ambient gas conditions (e.g. density, temperature) [[17]] and the type of fuel (Biodiesel [[18]], oxygenated fuels and many more) that generate significant variations in composition and quality of the global spray. For that reason, conventional instrumentation and laser-optical techniques cannot completely characterize such dense spray like Diesel sprays are, and so, mass concentration, droplet size and velocity distribution with respect to space and time are not always reliable in such conditions. The large number of droplets present in some regions of the spray makes the light extinction so high that uncertainties of the experimental results become excessively high. In order to go deeper into these issues, an experimental characterization of the optical thickness of Diesel sprays is made in this work.

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The process of atomization of sprays is responsible of creating thousands of droplets with different diameters, which results in a laser intensity loss respect to the initial light intensity due to scattering. The optical depth (or optical thickness, τ) is basically the fraction of light that passes across such a turbid medium which has not been absorbed or scattered. For a medium containing scatterers, the optical depth can be described by the so-called Beer–Lambert law [[19]].

If the light intensities are considered, I_0 being the incident radiation and I the intensity after extinction, the following expression of the optical depth can be written [[20]]:

$$\tau = -\ln\left(\frac{I}{I_0}\right) \qquad (1)$$

Linne et al. [[9]] claimed that for such turbid media like the sprays are, the optical depth provides an approximation to the average number of scattering events occurring during the passage of light (e.g. if τ = 10 the average number of scattering events is roughly 10). The laser techniques generally used to analyze the sprays (e.g. PDPA, Mie scattering, LIF) are generally accepted to perform well for τ < 1. For higher values, the scattering of light would be too strong and would lead to large error [[9], [16]].

This paper proposes to study and quantify the optical depth in a DI Diesel spray by measuring the extinction of light crossing the spray at different locations. The spray being optically thick and the extinction too strong in most of the regions, a spray concentration model has been used in order to extend the results and the optical depth in these dense regions. The influence of several parameters like injection pressure or ambient density has been studied in this work and an analysis of the SMD influence on the □ results in the spray has been done.

The paper is structured in the following way, first, the experimental installations is presented; the next part shows the results and the limitations of such measurements. Then, a model to fit the results and go deeper into the spray is presented together with an estimation of the droplets Sauter Mean Diameter. Finally, the global results of the extinction tests are presented, a comparison with PDPA measurement is done and a discussion over the parameters influencing the results is proposed.

2. Optical depth measurements system

The experimental arrangement used to perform the optical depth measurements is outlined in Figure 1. This setup relies on line-of-sight extinction of light through the fully atomized region of the spray and does not account for the liquid core or non-spherical structures present in the upstream flow.

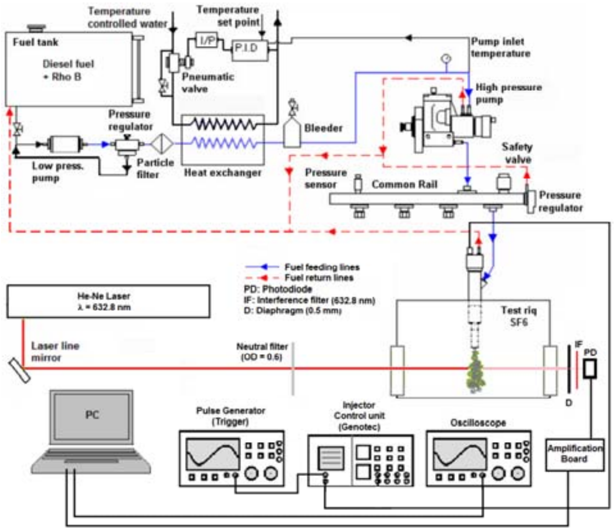

Fig. 1. Experimental installation scheme.

2.1. High-density chamber and injection system

Diesel sprays have been injected in a closed-loop constant pressure vessel filled in with SF6, which reproduces ambient densities existing in the real combustion chamber during injection at relatively low backpressure, due to the high molecular weight of the SF6 (around 6 times bigger than that of air or N2). In addition SF6 is an inert gas and its viscosity and optical properties are very similar to those of the air [[21]]. Experiments have been performed at three different densities inside the injection rig: 10 kg/m3, 25 kg/m3 and 40 kg/m3 with relatively low pressure: 1.7 bar, 4.2 bar and 7.05 bar respectively . Gas velocity inside the rig is controlled by a Roots compressor and was kept low (around 2 m/s in the measurement region) to minimize effects upon the spray, so that it can be considered that the fuel is injected in stagnant conditions, whilst the testing area is cleaned by the gas flow. A 10 cm long honeycomb has been used to avoid recirculation zones in the chamber. The injection chamber has three perpendicular optical accesses for visualization: two quartz windows to allow laser beam to get in and out respectively and one Polymethyl-methacrylate (PMMA) window placed at the top part of the testing area to provide easy visual access for user inspection. More detailed information about the high density injection rig is given by Payri et al. in [[22]].

A standard common-rail Diesel injection system was used at injection pressures of 50, 100 and 180 MPa. The injector is driven by a solenoid coil and is equipped with an axi-symmetrical single-hole nozzle with conical orifice so that the flow is non cavitating at the conditions tested [[23]]. The nozzle orifice has a nominal outlet diameter of 110 µm with k-factor of 1.8 and HE value of 10%. A regular Diesel fuel has been used, the fluid density is 836 kg/m3 at testing conditions. The injector energizing time has been set to 4.5 ms, this time should provide injections long enough to allow confident measurements in the steady part of the spray discarding data during transients [[24]].

2.2. Light source and collection

A 25 mW continuous wave He-Ne laser with a beam diameter of 1.2 mm at the exit and a beam divergence of 0.7 mrad is used as a light source for the optical depth measurements. At such wavelength (632.8 nm), light absorption by the Diesel fuel used is negligible. The forward scattering or light scattered in the incident direction is collected by a planar silicon PN photodiode directly connected to the amplifier board. The output signal is acquired by a digital oscilloscope (Yokogawa) connected to a PC for processing.

A neutral density filter has been placed to reduce the laser intensity and avoid saturation of the photodiode, and an interference filter centered at 632.8 nm (FWHM = 2 nm) has been placed as close as possible to the photo-sensor in order to remove undesired light. Just before the interference filter, a diaphragm with a diameter of 0.5 mm is used, which lets only the central part of the beam to reach the photodiode and improves measurement accuracy because only forward scattered light is acquired (collection angle is as low as 0.25 mrad which is within the range of divergence of the incident beam). The complete system (i.e. He-Ne laser, filters and photodiode) is placed on a XY computer controlled traverse to move the measuring section with high accuracy (Step distance = 80 µm ± 5 µm)

2.3. Digital acquisition system & procedure

For every injection event, data acquisition is triggered by the start of energizing and stops 10 ms later, the amount of data recorded during this time is 1000 which means an acquisition rate of 10 µs, which is three times longer than the rise time (or fall time) of the high-speed photodiode used (around 3 µs). As enounced before, the injector energizing time is set to 4.5 ms, and the hydraulic delay was found to vary from 295 µs to 350 µs depending on the injection pressure [[23]]. The actual injection time has been analyzed through spray momentum measurements [[24]] at the different conditions. Figure 2 shows the signal acquired through spray momentum measurement for 100 MPa injection pressure and 25 kg/m3 ambient density. Three major periods can be detailed on this graph, first a transient stage corresponding to the injector's opening, then a steady period and finally another transient corresponding to the closing of the injector and thus the end of injection. Data used in this work only consider the steady period as the transient part present complex parameters and structures than cannot be analyzed by such a line-of-sight optical technique.

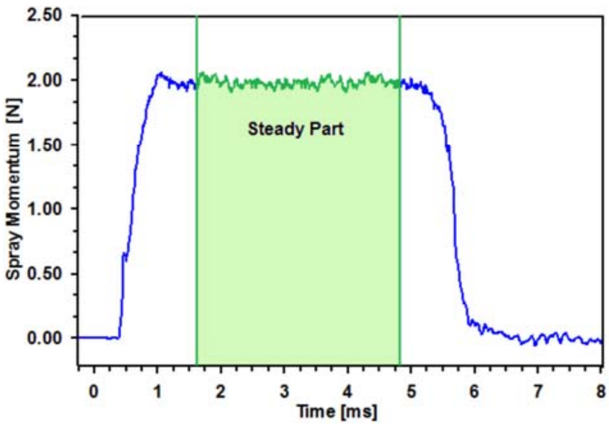

Fig. 2. Momentum flux of the spray at 100 MPa and 25 kg/m3.

The incident light goes through the steady part of the jet and the residual light goes through the small aperture of a diaphragm to ensure only forward scattering collection and then acquired by the photodiode. The measurements are performed at three axial distances from the injector tip: 20, 30 and 40 mm. At each distance, the system has been moved radially every 0.5 mm on both sides of the axis of the spray, a representation of the measurement locations is sketched in figure 3.

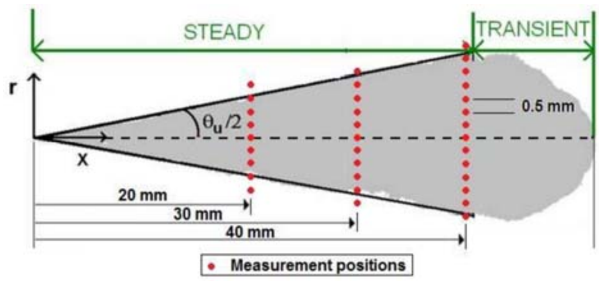

Fig. 3. Optical depth measurement locations in the spray.

The results have been processed over an average of 100 injection events leading to an overall maximum coefficient of variation as low as 0.049. This statistical analysis shows that the process of averaging 100 events provides results with really low dispersion and therefore high repetitiveness and accuracy.

3. Data processing and raw results

The graph presented in figure 4 shows the raw signal acquired by the photodiode for a single injection event, the signal processed (average of 100 injections), and the signal without injection as a reference. The latter shows that "slight oscillations" in the photodiode signal are present even when there is no injection, which maybe associated to scattering of the few droplets that may remain in the rig from previous injections or to slight refractive index variations associated to flow nonhomogeneities in the chamber. In any case, the variation on intensity induced by such noise is low enough to be neglected. The shape of the average signal reflects the same temporal evolution of the spray already commented in figure 2 with a clear steady part after a short transient period [[25]].

On figure 4, the different stages of the development of a Diesel spray are represented: First, the hydraulic delay (time between start of energizing SOE and the real start of injection SOI) together with the delay between the SOI and the moment when the spray reaches the measurement location (in this case 20 mm). When the head of the spray crosses the laser, the signal drops down drastically; it has been observed that the head of the spray has a higher fuel mass fraction [[26]]. Then the steady part of the spray (part used for the analysis) arrives at the measurement location and generally lasts at least 3 ms (due to the Energizing Time used in the present work). The smooth signal attenuation decay (i.e. light intensity increase) after the end of the injection is logical since many low momentum droplets scattered laser light until they are scavenged by the gas flow, but obviously, this part of the signal is completely useless for the purposes of this study.

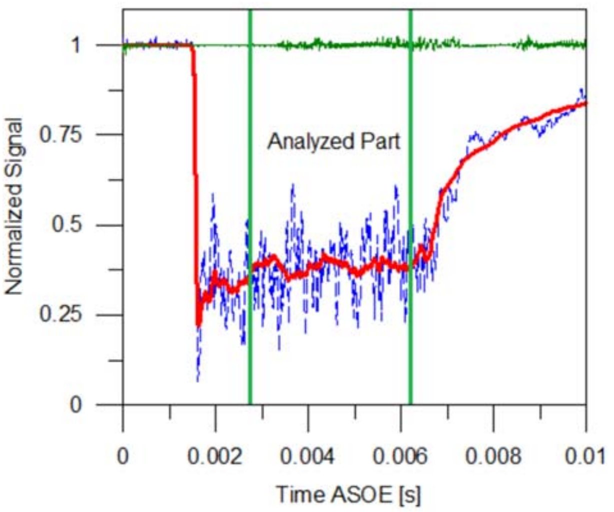

Fig. 4. Raw signal and processed signal (P_i = 50 MPa, ρ_g = 10 Kg/m^3, x = 20 mm and, r = 1.5 mm).

To determine the level of the light intensity of the steady part of the spray, two points are automatically selected; the first one is picked after the spray head has passed (roughly 1 ms after the minimum level reached by the spray head) and the second one is picked at the end of injection. Then, the intensity level is the average of the signal between these two limits. The spray head has a higher concentration, and even though it is interesting to study the concentration in this region, the spray head is too unstable to be correctly analyzed and quantified through line-of-sight extinction measurements.

The optical depth measured at the middle density case (25 kg/m3) for the three injection pressures tested in this work is shown in figure 5. A red line has been placed on the figures to show the limit of the τ that has been enounced (0 < τ ≤ 1) by other authors [[9]].

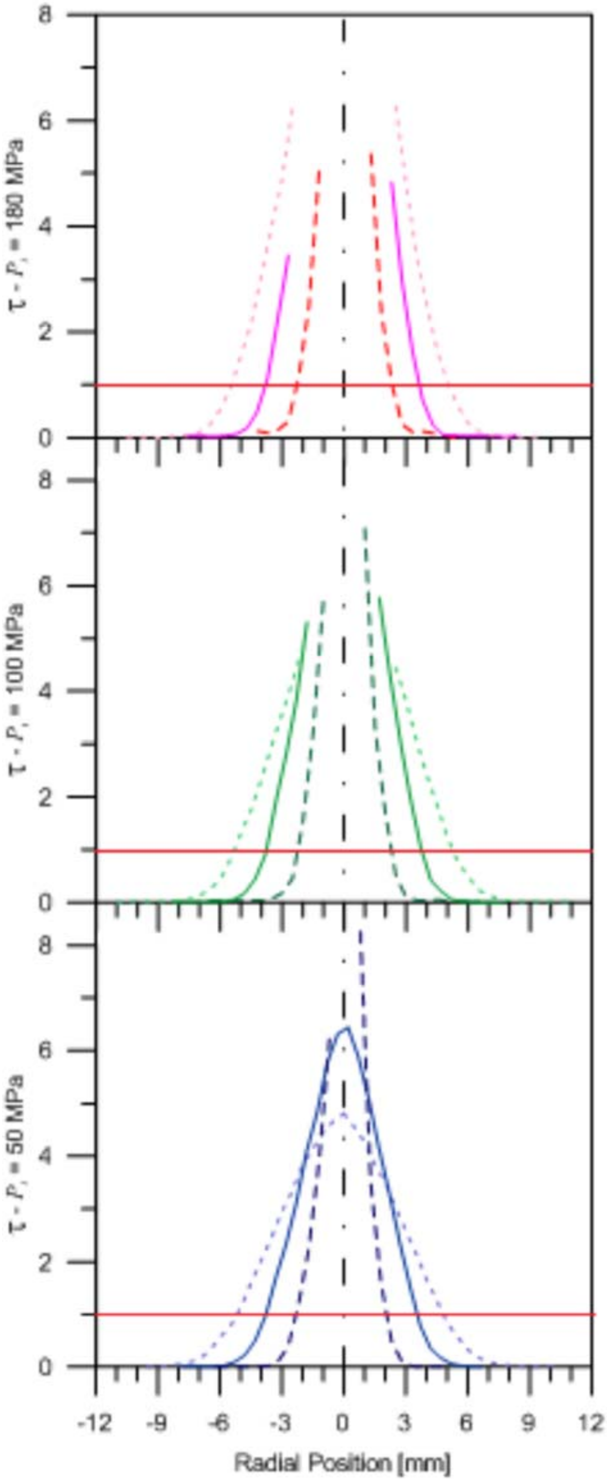

Fig. 5. Measured τ at three injection pressures, 25 kg/m^3 discharge density and at three distances from the orifice exit (long dash: 20 mm, solid: 30 mm and short dash: 40 mm).

The experimental results presented in Figure 5 only show the values that have been considered valid following a quite strict criterion: When the signal acquired by the photodiode in the steady part of the spray dropped below the noise level that

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particular injection event has not been considered in the averaging; if, as a consequence of such data rejection, the final amount of valid injections led to a relative standard deviation above 5%, the whole set of data in that measurement position has not been considered valid and is consequently discarded for the final processing.

Looking at figure 5 the results of the optical depth measurements are promising. On the one side, the general structure of the spray as depicted from the extinction measurements, with spray width increasing with axial distance, is consistent with the nearly conical shape of the spray seen from previous spray imaging studies [[7]]; on the other side, despite the very strict criterion used to reject doubtful data, optical depth values as high as 8 have been validated at some measurement positions and values of τ lower than 3.5 have always fulfilled the validation criterion independently of measurement position or injection condition. In central regions of the spray where experimental data are not considered accurate enough, at least estimation is pursued by refining the methodology on the basis of comparison of the experimental results with predictions given by a Diesel spray model detailed in the following section.

4.Theoretical analysis

The simple relation between light intensity losses and optical depth has been enounced in the introduction. As the aim of this work is to present results of the optical depth at every location in the spray, a Diesel spray model will be used to extrapolate the extinction values where the experimental measurement accuracy has shown to be limited. First, a procedure for the calculation of the optical depth will be derived from theoretical arguments, making special emphasis on the hypotheses assumed; then a spray concentration model to be fitted and used for estimations of τ near the spray axis is presented.

4.1. Optical depth calculation

For many liquid in the visible spectrum, absorption is negligible and so light extinction is only due to scattering. As commented before, the fuel tested has no absorption at the wavelength used in these tests. Considering monodisperse spherical particles, the optical depth derived from the Beer-Lambert law given in equation (1) relates to the particle scattering cross-section σ_e, the number density *n* and the path length *l* [[27]]

$$\tau = \sigma_e.n.l \tag{2}$$

The extinction cross-section (σ_e) is a function of the diameter of the droplet and is given by:

$$\sigma_e = \frac{\pi.D^2}{4}.Q_e \tag{3}$$

where D is the droplet diameter and Qe the extinction efficiency of the droplet (or particle). In the particular case of a Diesel spray, it seems reasonable, taking into account the typical droplets diameter distribution, to consider the extinction efficiency as constant for all the experiments and equal to 2.1 [[28]] (It is actually oscillating between 2 and 2.5 with droplets of diameters from 5 to 50 μm at 532 nm [[29]]). The number density (n) is the number of particles present in the volume considered for the calculation and can also be expressed as follows:

$$n = \frac{N}{V} \tag{4}$$

Here, N is the total number of particles within volume V. Finally, the path length l is the thickness of the spray at the measuring location and can be obtained through macro-visualization and assuming axial symmetry for the Diesel spray.

In a spray, the droplets have different diameters and, considering polydisperse spherical droplets, parallel diffusion and neglecting multiple scattering, a general expression of the optical depth can be written as:

$$\tau = -\frac{1}{V}\sum_{i}^{n}\frac{\pi.D_i^2}{4}.Q_e.l \tag{5}$$

Introducing the volume fraction (ϕ_f), as:

$$\phi_f = \frac{\sum_{i}^{n}\frac{\pi.D_i^3}{6}}{V} \tag{6}$$

and Sauter Mean Diameter (D32), as:

$$D_{32} = \frac{\sum_{i}^{n}D_i^3}{\sum_{i}^{n}D_i^2} \tag{7}$$

A new expression for optical depth is obtained:

$$\tau = \frac{3}{2}.\phi_f.Q_e.l.\frac{1}{D_{32}} \tag{8}$$

As the densities of the fuel (ϕ_f) and the ambient gas (ρ_g) are known, the fuel mass fraction can be calculated from the fuel volume fraction and the expression of the optical depth becomes:

$$\tau = \frac{3}{2}.Q_e.l.\frac{C_f.\rho_g}{\rho_f - C_f.\rho_f + C_f.\rho_g}.\frac{1}{D_{32}} \tag{9}$$

Thus, the optical depth is now expressed as a function of fuel mass fraction and the Sauter Mean Diameter (D32 or SMD); this parameter is widely used to define the average size of an ensemble of droplets.

4.2. Spray concentration model

As stated at the beginning of this paper, the first results of optical depth measured in the Diesel spray will be compared and then fitted with a spray concentration model to estimate τ wherever the quality of the signal were not good enough to trust the experimental results. This model, presented by Desantes et al [[25]], is based on the conservation of momentum in the axial direction and assumes Gaussian radial distribution profiles for both velocity and mass fraction according to the turbulent gas jet theory, which is commonly accepted to describe certain aspects of modern Diesel sprays [[25]]. Using this model the velocity on the spray axis at any axial distance x to the nozzle exit can be expressed (Eq. (11)) in terms of outlet spray momentum M0, ambient density ρg and spray cone angle θs

$$U_{axis} = M_0^{1/2} \cdot \left(\frac{2\alpha}{\pi\rho_g}\right)^{1/2} \cdot \frac{1}{\tan\left(\frac{\theta_s}{2}\right)} \cdot \frac{1}{x} \tag{10}$$

being α the fuel distribution coefficient. A value of α = 4.605 is used as proposed by other authors [[25], [30]] for the Gaussian profile. The relationship between velocity and fuel concentration (Cf) for Schmidt number (Sc) equal to 1 is expressed by equation (11):

$$C_{f\,\mathrm{axis}} = \frac{U_{axis}}{U_0} \tag{11}$$

where U_0 is the fuel velocity at the orifice exit given by Bernoulli equation. Once fuel concentration on the axis is calculated, fuel concentration at any radial position (the r/R ratio is the relative radial distance) is obtained from equation (12) where Gaussian profile is assumed.

$$C_f(x,r) = C_{f\,\mathrm{axis}}(x).\exp\left(-\alpha \mathrm{Sc}\left(\frac{r}{R}\right)^2\right) \tag{12}$$

This model is valid once the liquid is fully atomized and this is the region of interest, as long as the measurements have not been performed close to the orifice exit (closer location is 20 mm away from the tip in our experiments). The input parameters used in the model to simulate different conditions of the injection process that are typical of modern Diesel sprays [[3]] are the same used during the extinction measurements; the spray cone angle has been measured through spray imaging in the same test rig at the same conditions.

Results of the fuel mass fraction obtained by the model for an injection pressure of 100 MPa and a discharge density of 25 kg/m3 are shown in figure 6.

Combining equations (9) and (12), it is possible to estimate the optical depth from the fuel concentration given by this model as long as the Sauter Mean Diameter is known and contrast this information with other experimental results of droplet size. However, since information on SMD must be obtained from other ways (PDPA system for example), which do not ensure high accuracy in optically thick media, a different approach is followed in this work. Instead of using as an input the SMD results measured by a PDPA instrument (cf. section 5) for the same conditions, the value of SMD is a result of the process of providing the best match between the model and the experimental measurements of τ given in figure 5. In other words, the droplet size (SMD) has been considered as a tuning parameter for the model in this work.

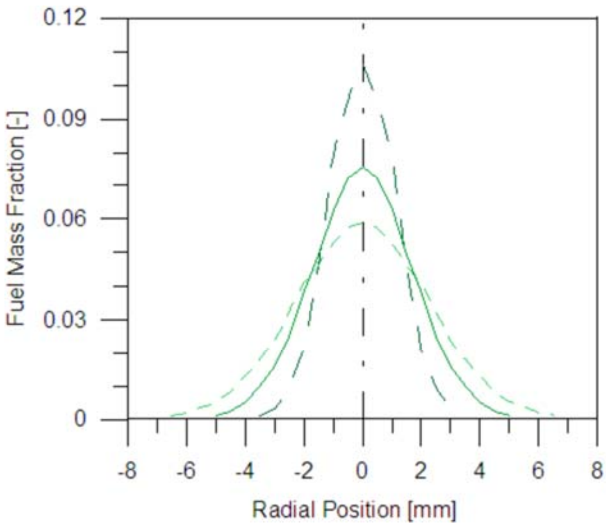

Fig.6. Model calculated fuel mass faction at P_i = 100 MPa and ρ_{gas} = 25 kg/m^3 (long dash: 20 mm, solid: 30 mm and short dash: 40 mm).

Experimental results of drop size measurements with the PDPA instrument reported in [[31]] revealed that SMD changes with injection conditions and axial distance but does not vary sensitively with radial distance. This means that extinction measurements when the beam travels through different radial positions would not be affected too much as a consequence of droplet size gradients. Consequently, a single SMD value has been estimated for every injection condition and axial distance, as the one that provides the closest match between model predictions and experimental optical depth results for all measurements taken at the different radial positions.

5. Estimated optical depth results

The results of optical depth obtained through light extinction measurement in a Diesel spray under the different conditions tested are compared to the predictions given by the diesel jet model presented before in figures 7 to 9. The goodness of the fit between the model and the experiments has been ensured through the coefficient of determination R2 to get the closest match between both approaches. The lowest value returned during the fitting of all testing conditions and locations is as high as 97.8 % with an average value of 99.3 % which demonstrate the ability of the model to fit the experimental results.

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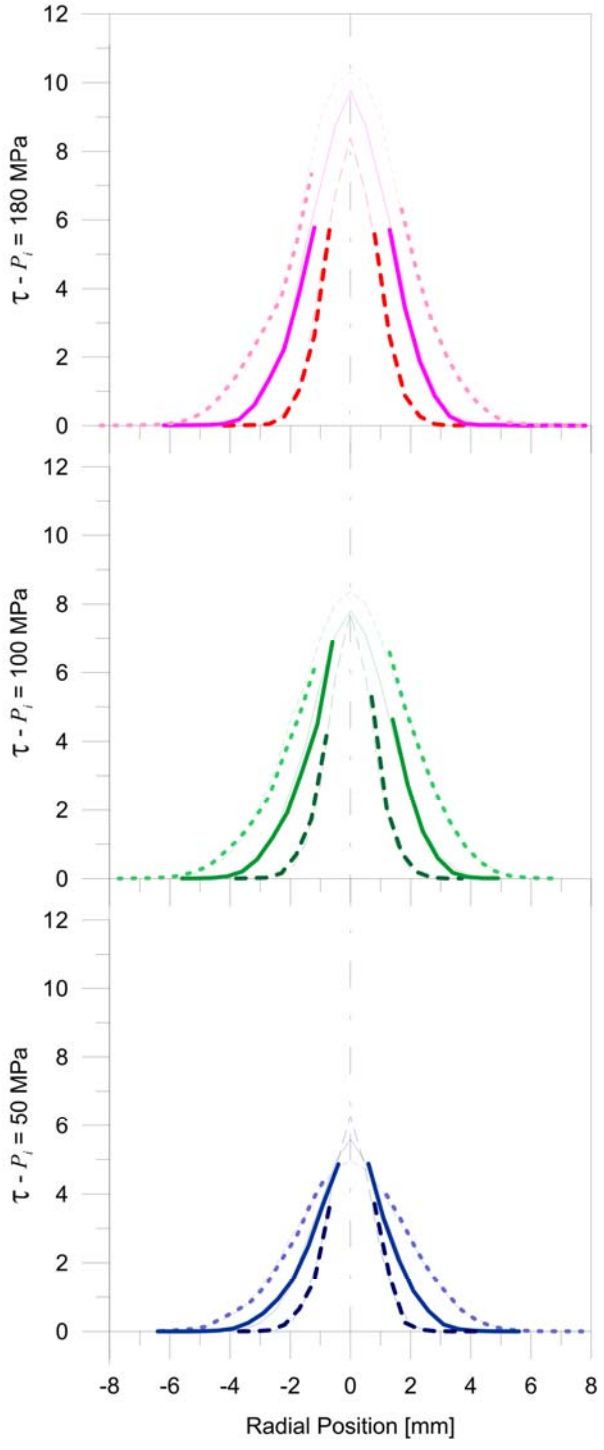

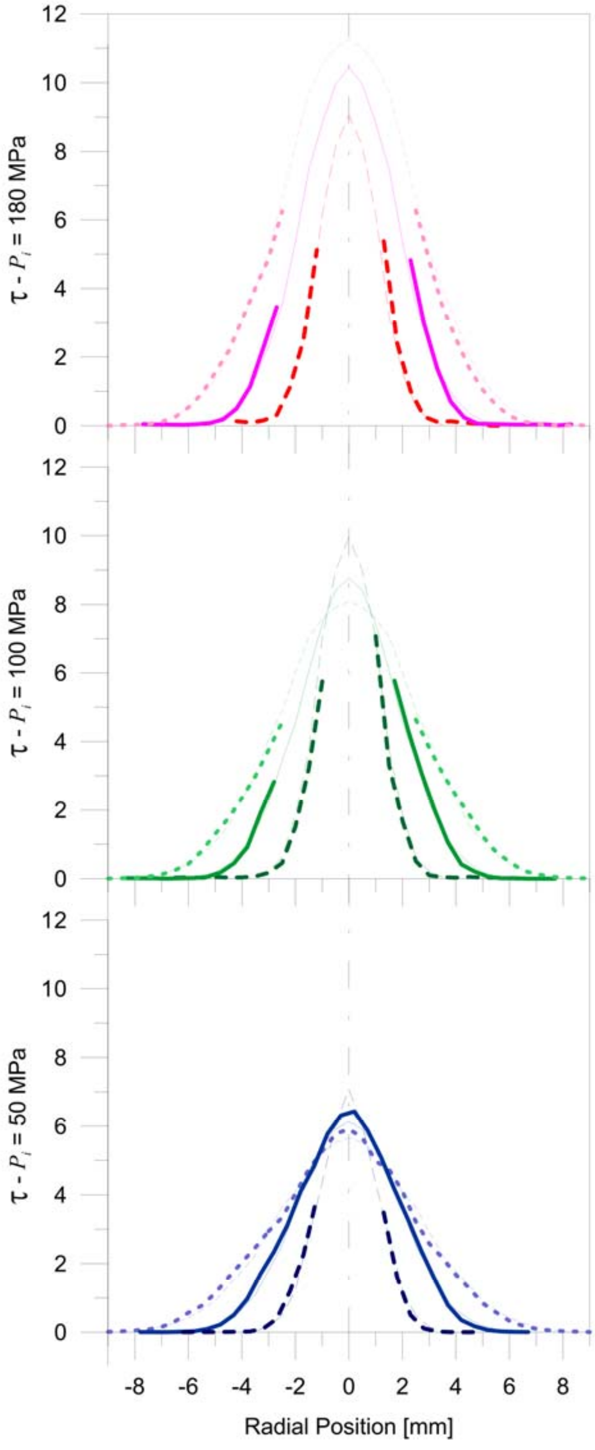

Fig.7. Measured and calculated τ at three injection pressures, 10 kg/m^3 discharge density and at three distances from the orifice exit (long dash: 20 mm, solid: 30 mm and short dash: 40 mm, thick line: experimental).

Fig. 8. Measured and calculated τ at three injection pressures, 25 kg/m^3 discharge density and at three distances from the orifice exit (long dash: 20 mm, solid: 30 mm and short dash: 40 mm, thick line: experimental).

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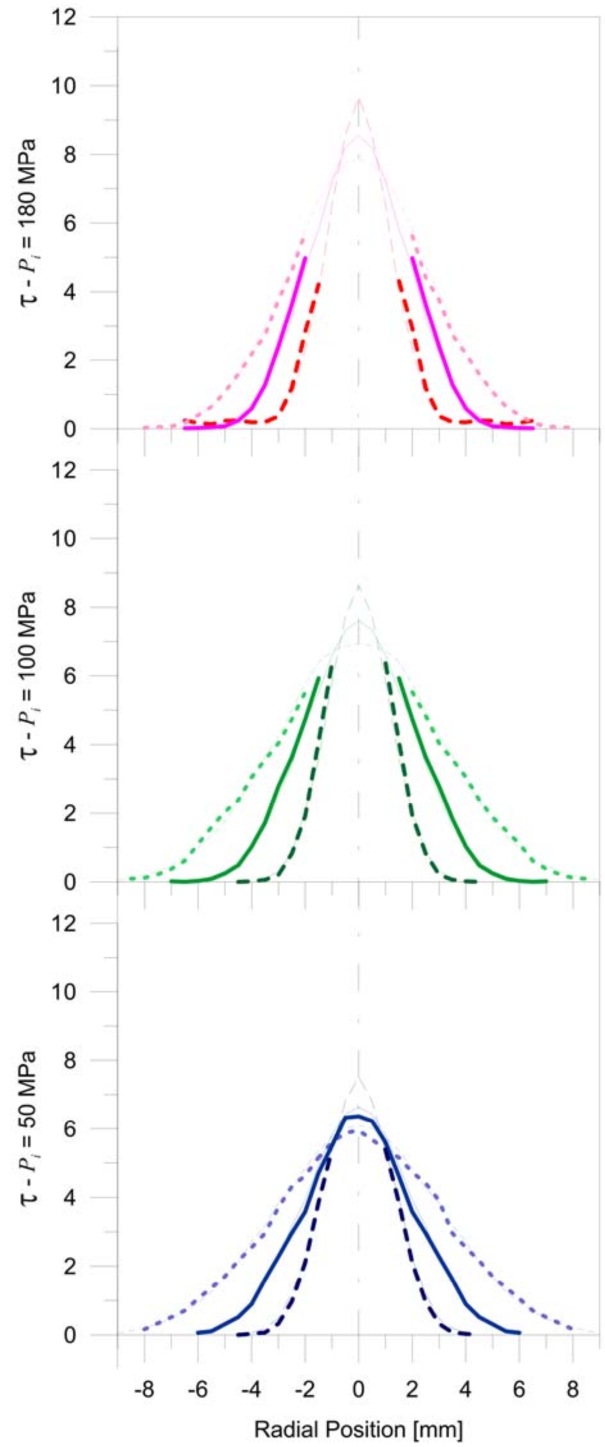

Fig.9. Measured and calculated τ at three injection pressures, 40 kg/m^3 discharge density and at three distances from the orifice exit (long dash: 20 mm, solid: 30 mm and short dash: 40 mm, thick line: experimental).

The values of the light extinction through an axi-symmetrical diesel spray are in agreement with experimental results already published [[28], [32]]. In addition, the latest advancements in spray modeling, using Monte Carlo simulations for example, show similarities in the extinction of light through liquid droplet in the less dense region of the jet that confirm the present results [[33], [34]]. According to the extrapolated results of the model, the optical depth in the center of the spray can go up to 11 which is generally considered as in the multiple scattering regime [[35]]. Such high optical depth values are typical of modern DI diesel sprays and make the study almost impossible without specific and expensive optical setup like those mentioned in the introduction. However, it is interesting to see that the experimental results agree pretty well with the model until only about a millimeter from the axis of the jet, then the extinction is too high and no reliable measurement can be processed. In this context the modeling approach can help to overcome the experimental limitation due to multiple scattering and the combination of experimental and computational solutions is a solid way to get quantitative and reliable results.

On this batch of graphs (fig. 7 to 9), the influence of the injection pressure on the optical depth appears clearly: higher injection pressure leads to higher τ. With the new injection technologies, the pressures are higher for a better atomization, this result in making the analysis of the jet more complex at microscopic level. However, the OD should be higher for location closer to the orifice, assuming a higher fuel concentration and therefore higher number density. But when the injection pressure increases and the discharge density decreases; the results show that this tendency is not necessarily followed. This can be explained by the fact that the process of atomization seems to last longer at high injection pressure and low discharge density. Based on a two-stage 1-D model proposed by Naber and Siebers [[36]], the development of the spray has different behavior before the breakup time, which can be assimilated as a breakup length under steady conditions by including the penetration rate. This breakup length to get a fully atomized spray [[36]] shows that the disintegration process would finish at a longer distance from the orifice at higher injection pressures. This may explain part of the observations made concerning the discharge density and the distance to the orifice.

Table 1 gives the actual output values of the droplets diameter when the model fits best the experimental data of the measured optical depth. These values are presented together with SMD results obtained at the same experimental conditions (testing section, injection system and conditions) through PDPA measurements as a comparison (see [[37]] for more details on the setup of the instrument). The testing locations of the PDPA have been selected to match those measured through extinction of light and the values presented in table 1 are an average of the PDPA punctual measurements across the spray (every 0.5 mm). An important thing to say is that the diameters found during the fitting of the model are always lower than that measured with the PDPA instrument; it has been particularly observed that when the pressure increases and to a lesser extent when the discharge density decreases, the diameters have not been accurately measured by the

PDPA. This confirms the limitations of this instrument when the droplets are numerous and small, other researchers related a poor data rate regarding the accuracy of the results when measurements are performed in a spray containing small droplets [[37]-[40]]. In the same way, a novel technique known as double extinction showed the ability to measure in denser region of the spray than PDPA does and generally provided lower SMD values than the interferometric technique [[41]]. Concretely, the error becomes too high with injection pressures of the order or higher than 100 MPa when the instrument is close to the orifice exit (20 mm); the poor data rate of the PDPA at this distance confirms the difficulties to measure in such an optically dense region.

Table 1. Sauter Mean Diameter (D32) of spray droplets for the tested conditions: Used to fit the model / measured with PDPA (values are presented in μm).

Axis Location [mm]	P_{inj} \ ρ_{gas}	10 kg/m^3	25 kg/m^3	40 kg/m^3
20	50 MPa	11.9/12.9	14.9/16.9	17.7/19.4
	100 MPa	8.9/11.3	12.0/14.8	13.7/17.0
	180 MPa	6.7/10.1	9.4/13.2	10.8/15.2
	P_{inj} \ ρ_{gas}	10 kg/m^3	25 kg/m^3	40 kg/m^3
30	50 MPa	12.7/14.2	17.1/18.6	19.0/21.4
	100 MPa	10.2/12.4	13.2/16.3	14.9/18.7
	180 MPa	7.6/11.1	10.3/14.6	11.7/16.7
	P_{inj} \ ρ_{gas}	10 kg/m^3	25 kg/m^3	40 kg/m^3
40	50 MPa	14.0/15.2	18.0/19.9	20.7/22.9
	100 MPa	10.8/13.3	14.0/17.4	16.2/20.1
	180 MPa	8.4/11.9	10.6/15.6	12.5/17.9

Both the effects of injection pressure and discharge density on SMD are graphically represented on figure 10. The plot demonstrates that when injection pressure increases, the average droplet diameter decreases, certainly due to a higher Weber number. The disintegration process depends on Weber number; at higher We the droplet disintegration rate is higher and this globally leads to smaller droplets in the jet. The Weber number depends on the fuel surface tension (σ) and density (ρ), the droplet diameter (D) and velocity (v) such as: $We = (\rho v2D)/\sigma$. The velocity increases with injection pressure resulting in higher Weber number and so greater disintegration rate. This trend has been observed by other researchers [[37], [38]] and has a direct impact on the optical depth of the spray. As explained in the previous section, the droplet diameter has been used as a tuning parameter to fit the model to the experimental data and therefore both magnitudes are related. In a lesser extent, the discharge density also affects the droplet diameter and thus the optical depth; lower discharge densities lead to smaller droplets, as seen stated in [[37], [32][38]]. In addition, at low discharge density, the spray is narrower and the interaction between the droplets in the spray is higher and secondary atomization due to droplets impingement can occur. And this fact is reflected in the optical depth results, since τ is a function of the total number of droplets in the analyzed region (related to the Number Density n and the path length l) and droplets diameter.

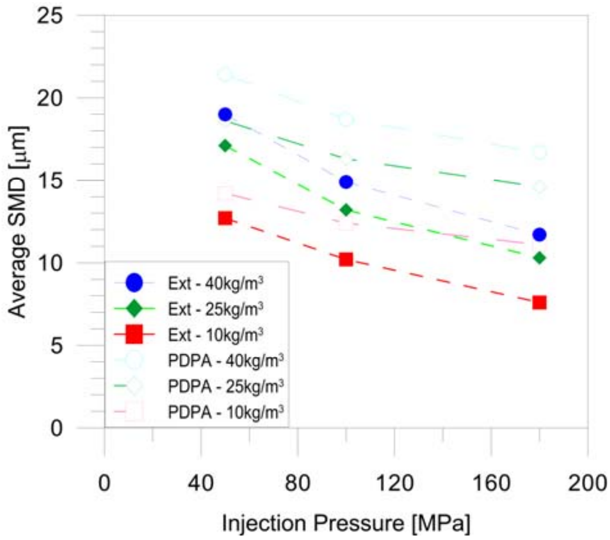

Fig.10. Average Sauter Mean Diameter at 30 mm from the tip through optical depth and PDPA measurements for different injection pressures and discharge densities.

One last comment is that the values of the optical depth on spray axis estimated with the combination experiment/model roughly go from 5 to 11; this means that almost all the standard techniques used to visualize the spray would not be reliable. These results are in agreement with the statements emitted by Berrocal [[35]] that when the light goes through a DI Diesel spray, the droplets are so numerous and small that the propagation of the light has to be treated as a multiple scattering regime. As enounced in the introduction of this paper, some correction techniques are available to partially correct the multiple scattering induced by the droplets in a dense spray as long as the light signal is not totally attenuated by the spray itself, but much work need to be done on this topic.

6. Conclusions

An estimation of the optical depth in a DI Diesel spray under different conditions is provided in this paper based on a combined experimental/modeling approach. Although it is normally accepted that optical measurements are reliable up to an optical depth around τ = 1, the results shown in this work reveal that the measurements have fulfilled the strict criterion imposed for the experimental data to be considered as valid for values as high as τ = 8.

A simple Diesel fuel spray concentration model has been used and adjusted to fit the experimental data, this association shows good agreement between experimental and calculated results. The model has extended the results throughout the spray at locations where the experimental data were not considered as valid and showed that the optical depth values on the centerline of the jet are generally going from 5 to 11 depending on the conditions (injection pressure and discharge density).

The SMD values used to fit the model show consistency with the experimental conditions, when the injection pressure increases, the droplets are getting smaller. Minor values have been obtained through this technique compared to those obtained with a PDPA instrument, probably due to the lack of accuracy of the interference detection system in these particular conditions such as dense spray and small droplets.

Finally, longer distances from the orifice exit do not show a decrease of the optical depth as expected, the results demonstrate that it is not always following this trend because the global atomization process occurs later and leads to higher optical depth. In any case, neither the distance from the orifice nor the injection pressure is leading to reasonable values of τ for accurate in-spray analysis without any correction except at some locations away from the spray axis.

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Professor Francisco Payri received his degree in Mechanical Engineering from the Technical University of Madrid in 1971, and his PhD from the same University in 1973. Teaching activities started in 1972 at the Escuela Técnica Superior de Ingenieros Industriales (Mechanical Engineering School) in Madrid. In 1979 he moved to the Technical University of Valencia, becoming a full professor in 1983. Prof. F. Payri has been the head of CMT Motores since 1986. Member of the Scientific Coordination Commission of the Institut Français du Pétrole (France) since 1999 and Fellow Member by the Society of Automotive Engineers of the USA since 2008

Dr. José V. Pastor, graduated in 1991 as a Physicist, completed his PhD thesis on internal aerodynamics in Diesel engines in 1996, and has participated in more than 100 R&D projects with public or private funding in the automotive sector including several contracts funded by the European Commission. Currently he is a permanent professor at Universidad Politécnica de Valencia and leads a research division on Optical Diagnostics at CMT-Motores Térmicos. He has published more than 50 papers in scientific journals and renowned international conferences.

Professor Raul Payri graduated as Mechanical Engineer in 1995, received his phD in Mechanical Engineering in 1999 from the CMT-Motores Termicos (Thermal Engines), Universidad Politecnica de Valencia, Spain, where he has been professor since 2000. Over the last ten years he has coordinated and participated in 35 competitive projects funded by European Union and national administrations and more than 60 R&D projects funded by the industry. He has published 32 articles in international Journals and 35 papers at international and national conferences. He has been supervisor of four Doctoral Theses. Nowadays Dr. R. Payri is the head of the injection research group at CMT-Motores Termicos

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Mr. Julien Manin graduated as a mechanical engineer in a state school in France in 2006. He got a Master's degree in vibro-acoustic the same year and a Master of Science in transportation systems in 2009. Since 2007, he is researcher at Universidad Politecnica de Valencia, Spain where he plans to finish his PhD in 2010. He has worked in the field of sprays and laser diagnostics and participated in several research projects with renowned institutes. He was granted by the Spanish Ministry of Science and Innovations and he is an active member of the ECN Working Group.

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