EXTERNAL AND INTERNAL BEHAVIOR OF THE NEAR FIELD DIESEL JET AT HIGH INJECTION PRESSURE : DUAL SOURCE VISUALIZATION AND MULTIPLE ANGLES TOMOGRAPHIC EXPERIMENTS.

J. Yon, J.B. Blaisot and M. Ledoux
CORIA-UMR 6614 : CNRS, Université et INSA de Rouen
Site universitaire du Madrillet, avenue de l'université
BP 12 76801 Saint Etienne du Rouvray, France
Phone : 33.(0)2.32.95.36.76 / fax : 33.(0)2.32.91.04.85
jerome.yon@coria.fr jean-bernard.blaisot@coria.fr michel.ledoux@coria.fr

Abstract
Much progress has been made in the field of Diesel injection techniques since the past twenty years. The injection pressure increased by a factor 10 thanks to the coming appearance of the common rail system and to the change in the injector geometry. Droplet sizes have been reduced as well as emission of CO_2 and NO_x. Industrials still need for numerical tools to assist the conception of injectors. To create virtual injector configuration the manufacturers need models for the diesel jet at injector's outlet. At the present time, there is no unified assessed model for the Diesel jet and different points of view can be found in the literature [1][2]. In this paper, we present near field jet visualizations obtained from the use of two synchronized light sources : a coherent laser source and a non-coherent white pulsed source. Different configurations of the laser light sheet tomography setup were explored. The use of ray tracing help us to interpret the light scattering patterns obtained. For a certain range of delay time and injection pressure, the images present line structures which are related to the presence of gas cavities. These visualizations allowed us to gain an insight into the way the Diesel jet emanate from the nozzle and to propose a model for the dense core.

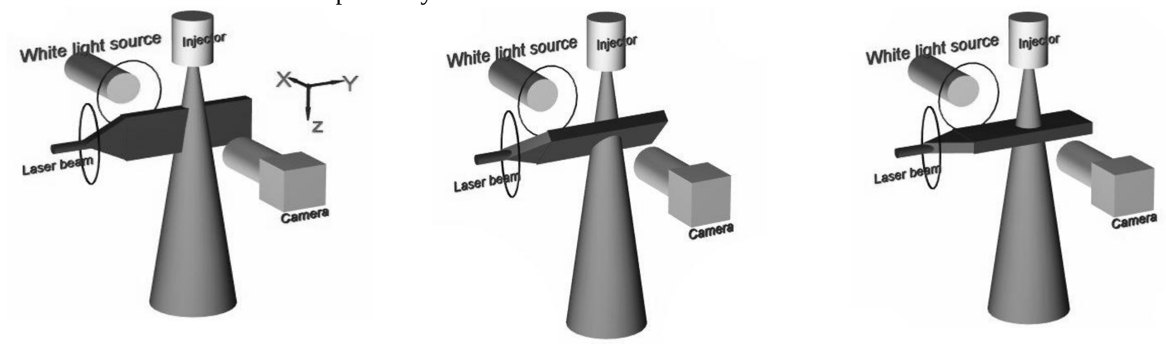
Introduction
Decreasing the pollutant emissions from diesel engines is a challenge for many scientists and engineers including the spray community. The knowledge of the Diesel jet atomization process is thus essential to control the Diesel spray formation and thus to optimize the fuel combustion.
The structure of a Diesel jet in the near field of the nozzle is explored experimentally.
This part of the jet is very difficult to study for many reasons:

- It corresponds to a field less than 1 mm^2;
- the high injection pressures employed in direct injection engines induce simultaneous complex atomization processes and high liquid velocity penetration;
- the injection is strongly time dependent, with very short duration;
- the optical density of this part of the spray is very high;
- The structure is extremely complex, owing to the probability of cavitation and strong turbulence at the injector outlet.

Numerous imaging techniques have been tested for this experimentation. The backlighting imaging with flashes of very short time permits to freeze the interface of the jet but not inform on the internal flow. The other main technique considered as the most promising one is the laser light sheet tomography. This technique seems to be the best one to bring out information from the Diesel dense core. A vertical laser sheet pointing the jet was previously used by Fath [4], Cavaliere [5] and Tamaky [6] among others, to obtain Mie-scattering imaging. But the interpretation of this kind of image require an initial knowledge of the jet structures. At present time, it is not possible to conclude clearly on the nature of the Diesel jet at the outlet of the injector and different schemes are always under discussion : either the jet is spontaneously atomized [2] or a liquid core is still present in the vicinity of the nozzle [1].
It is attempted here to collect enhanced experimental data. In this scope, we extend the capabilities of the laser tomography by combining it with backlighting. An original feature of this study lies in the way the laser sheet is positioned in the jet : Different angles between the jet axis and the sheet where explored.

Experimental setup

In order to simplify the observations we used a single vertical axis orifice whose diameter and length are respectively 200µm and 800µm. The injection pressure P_i ranges from 10 to 80 MPa and the ambient pressure is kept at atmospheric level. The needle lift is electrically driven at the starting injection time T_0. The needle position is also controlled during the injection time. Two types of light source of very short duration time (10 ns) are used to illuminate the jet at different delay time η relative to the injection command time. A 30 mJ coherent laser YAG (λ=532 nm) is used to provide a light sheet about 50µm in thickness. The Mie scattering tomography technique provides information about the internal structures of dense jet core. A white incoherent flash lamp (Nanolite) is used in a backlight configuration. A Sony CCD camera coupled with a long working distance microscope provide a field of view around 620*472 µm. The camera is vertically oriented in order to present the larger CCD side along the axis of the jet (each component of the setup can be freely moved, relatively to the other). The originality of our approach resides in the way the laser light sheet is placed. The three optical configurations used in this paper are shown in figure 1. The configuration A is a classical tomography configuration with a vertical laser light sheet orientation. For configurations B and C the laser sheet is tilted 45° an 90° from the vertical axis respectively.



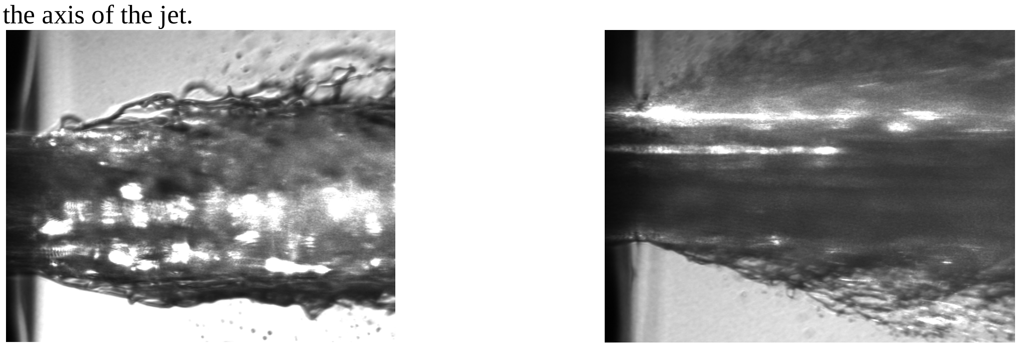
Configuration A : vertical laser light sheet orientation. Configuration B : 45° light sheet orientation Configuration C : horizontal light sheet orientation

Figure 1. Experimental set-up orientation

Results and Analyzis

Configuration A

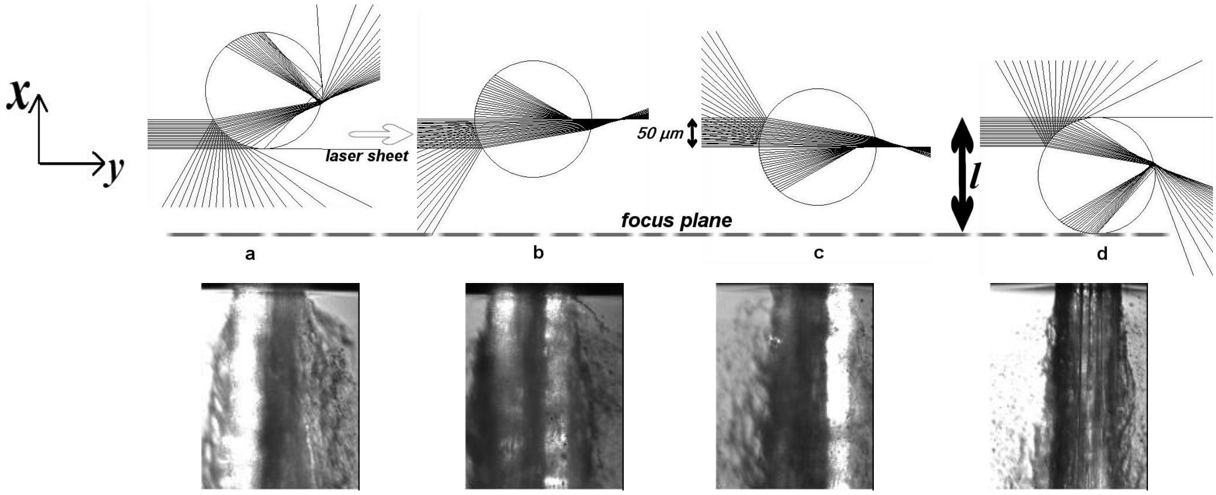
Two injection pressures (20 MPa and 80 MPa) at the same injection time (η=2.19 ms) are presented in figure 2 for the configuration A. The laser light sheet and the focus plane are of the camera are superimposed and intercept the axis of the jet.



P_i=20 MPa P_i=80 MPa

Figure 2. Images from the configuration A, η =2.19 ms

One observes a change in the external structures of the jet with the injection pressure. At a low injection pressure large ligaments surround the liquid jet. These ligaments are principally formed from the liquid bulk disintegration. Liquid sheets are also observed. For P_i=80 MPa, the destabilization processes become more intense. A persistent liquid sheet is always formed at the same location (on the left part of the jet). This is probably due to local orifice defects. High liquid velocity induces Kelvin-Helmoltz instabilities which rapidly disintegrate the liquid sheet into ligaments and finally into into fine droplets of diameter lower than 10 µm. The light scattered from the laser sheet presents two different patterns depending on the injection pressure. For P_i=20 MPa, a great light flux is directly reflected by the corrugated liquid-gas interface.



$$l = 175 \pm 50\,\mu m$$

Figure 3. Ray-tracing model with corresponding images, P_i=30 MPa η=2.19 ms

For P_i=80 MPa, straight lines appear in the scattering light pattern. At this high injection pressure there is no more liquid-gas interface. At least a dense two phases flow including ligaments and sheet replaces the continuous liquid-gas interface. On may conclude that the observed scattered light pattern is related to internal flow structures. These straight lines were observed for P_i≥25 MPa. The position of the laser sheet relative to the vertical axis of the jet, Δx has been varied. Images corresponding to four position Δx, P_i=30 MPa and η=2.19 ms are shown in figure 3. In this particular case, the focus of the camera varied. The focus plane is shifted within a distance l in the x direction. The different light patterns observed in this configuration are explained with the help of ray-tracing computation. A cylindrical column of gasoil and of diameter d=200 µm is considered. The surrounding spray is not taken into account but an important light scattering is expected if the light is focusing in this media. On figure 3, dashed line indicates the position of the focus plane. In the case a, the laser sheet is directly reflected on the left part of the plain liquid phase. The surrounding spray scatters the reflected light behind the focus plane which explained the luminous blurred aspect of the left part of the corresponding image. In the case b, the reflection on the left part of the jet still exist and the rays refracted by the jet interface are focused on the right part of the jet. The light is then scattered by the surrounding spray on the left and right part of the jet. The focus plane is nearer from the jet than previously and some droplets, back-lighted by the scattered light are visible. In the case c, the light is reflected towards the +x direction. The left part of the light scattering is obscured by the jet and the surrounding spray then no more visible but the right luminous part remains. In the last case, the right positioned focused point disappears, and a part of the refracted light is expected to cross the interface of the jet towards the camera. Then the black thin light observed on this image would be internal structures shadows positioned on the peripheral part of the liquid jet. This model seems to be in accordance with the experimental data from a qualitative point of view. So, this shows that, to have a better visualization of these structures, we must shift the camera in order to be focused on the peripheral part of the jet. The obtained image is presented in figure 4.

Configuration B

In this configuration the laser sheet plane intercept the jet with an angle of 45° with respect to the vertical axis. The principal interest of this configuration resides in the fact that the scattering pattern contains information about the entire jet. The drawback is that the interpretation seems more difficult (figure 4-a). But, by considering ray-tracing model exposed above, the reconstruction of the images could be done. The reconstruction method is illustrated in figure 4-b.

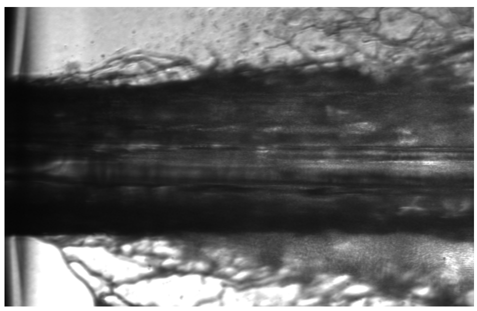
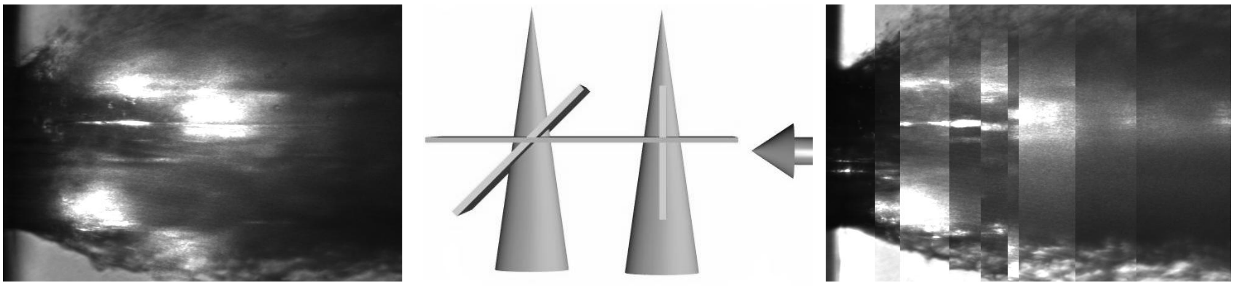


Figure 4. View with a shift of the focus plan



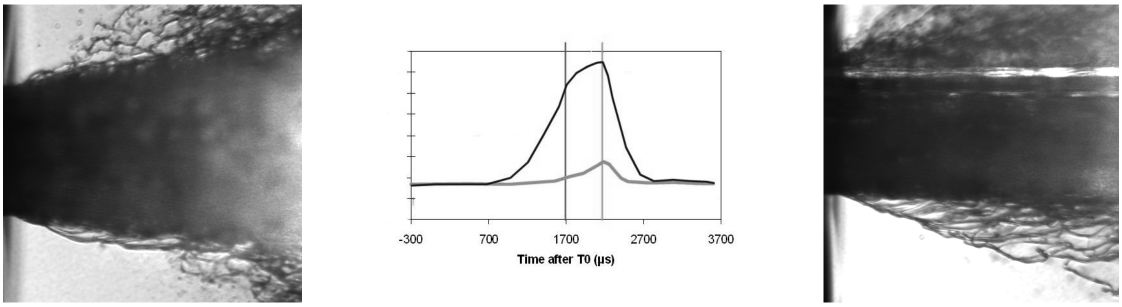
a : 45° illumination image b : Reconstruction method c : Reconstructed image

Figure 4. Reconstruction of the pictures obtained with the second configuration, P_i=80 MPa, η=2.18 ms

The orientation of the laser sheet implies that for each *z* position in the image corresponds a different *x* position of the laser sheet impact into the jet. Thus several slices coming from the first experiment (configuration A) are put end to end in order to reconstruct the image of the configuration B. The result is represented in figure 4-c. The characteristic pattern observed on the original image a is reconstructed in figure b. The only change comes from the change of focus plane for each slice of the reconstructed image whereas the focus plane naturally does not change for the 45° laser sheet orientation.

Configuration C

Images of the configuration A present linear structures when P_i≥25 MPa. The nature of these long linear structures remains unknown in term of both temporal and spatial aspect. In the configuration C, the laser sheet is oriented horizontally and located just below the camera field of view. The laser energy has been increased to observe the light propagation in the jet. The results presented here correspond to the P_i=40 MPa with the focus plane centered in the jet. The two photos presented in figure 5 are obtained for two different injection times (η=1.77 ms and η=2.17 ms).



***η* =1,77 ms** Needle lift time representation ***η* =2,17 ms**

Figure 5. Results of the configuration C for two different injection time, P_i=40 MPa.

At the beginning of the injection, large ligaments are present. Some liquid sheets arise in the left part of the jet (bottom part on the image). At a later injection time, the flow is quasi-stationary, the liquid sheet is totally developed. The observed waves on the liquid sheet positioned on the left part of the jet, corresponds to the ligaments formation for higher injection pressures. The scatter light patterns of the two images are totally different. For the η=1.77 ms, a spatially homogenous light scattering occurs. This is in agreement with the hypothesis of a homogeneous emulsion of gaseous inclusions inside the jet. This interpretation is coherent with previous observation made by Soteriou [7] in a scaled up plain orifice nozzle. When the jet is fully developed (η=2.17 ms), a straight line appears in the image. This indicates that the previously observed act like optical guides so these structures correspond to a change of the media. This makes us believe that the structures are long tube-like shape gas cavities. This type of cavitation was observed in transparent nozzles by Arcoumanis et al. [8]. They showed the presence of gas films at the nozzle wall. At the outlet, this pockets gives birth to gas ligaments. The presence of cylindrical gas cavities was mentioned by Fath et al. [9]. The observation of these luminous lines structures occurs for sufficiently high injection pressure. This is coherent with the idea that cavitation structures need a minimal injection pressure for the cavitation number to be higher than the critical value.

To validate the hypothesis of tube-like shape gas cavities, we calculated the time of collapse of a gas bubble from the Rayleigh equation (1). One can note than this equation considers spherical bubbles and not cylindrical ones but, this gives us an order of value.

$$\left(T_i = 0.915 \cdot R_o \cdot \sqrt{\frac{\rho}{P_\infty - P_v}} \right) \quad (1)$$

where R_0 is the initial radius of the germ responsible for the cavitation appearing, ρ is the liquid, P_∞ is the pressure at infinity in the liquid. P_v is the saturated vapor pressure of liquid. The calculated time of collapse is 0.42 µs with R_0=5 µm which is a value commonly used in the literature. The velocity of the liquid in the quiescent air is in the order of 200 m/s so, considering spherical shape cavities, we can estimate the distance they cover to be around 85 µm. This corresponds to the order of the structure length observed.

Proposed scheme for the Diesel dense core

Tube-like shape cavitation bubbles have also been observed with the non-coherent backlighting only. In this case, some image processing (gamma correction, contrast enhancement …) are needed to visualize the straight structures. It has been shown through specific calculation [10] that these lines can be produced by cylindrical gas cavities located at the periphery of the liquid jet. The light distribution diagrams obtained by ray-tracing computations present discontinuities similar to what is observed on the images.

The scheme proposed here assumes the existence of a liquid core at the nozzle outlet. For injection pressure higher than 25 MPa and for quasi-stationary flow conditions, two kinds of gas cavities can be encountered. The first collection of cavities constitute an homogeneous cavitation foam. The second kind is showed of tubular shape along the jet axis positioned on the jet boundary (figure 5).

Figure 5 : Model of the dense core. For P_i≈50 MPa

Conclusion

Backlight and different tomographic configurations were employed simultaneously to visualize the Diesel jet at the outlet of the nozzle. The originality of this approach lies in the use of two angular configuration of the laser light sheet. The focus plane position was varied to observe lines structures in the jet. Different injection pressures and injection delay time were used. A ray-tracing simulation helped us to interpret the observed patterns of light scattering. The different approaches permit to elaborate a model for the Diesel jet at the nozzle outlet. The jet is composed of a liquid phase containing gas foam and tube-like shape gas cavities very long (>1mm) with diameter in the order of 10 µm positioned in the jet periphery.

These structures has been visualized also with the unique backlighting non-coherent source. As this configuration is very easy to implement, it seems very promising and will be used to achieves further experiments on the near field of the Diesel jet.

Nomenclature

x, *y*, *z*	spatial directions,
d	nozzle diameter,
P_i	injection pressure,
P_v	saturated vapor pressure of Diesel fuel,
T_0	injection command time,
R_0	initial radius of the germ,
η	illumination time after T_0,
ρ	Diesel fuel density,
λ	wavelength of the laser light.

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