

Study of the Mixing and Combustion Processes of Consecutive Short Double Diesel Injections

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ABSTRACT

The mixing and combustion processes of short double Diesel injections are investigated by optical diagnostics. A single hole Common Rail Diesel injector allowing high injection pressure up to 120MPa is used. The spray is observed in a high pressure, high temperature cell that reproduces the thermodynamic conditions which exist in the combustion chamber of a Diesel engine during injection. Three configurations are studied: a single short injection serving as a reference case and two double short injections with short and long dwell time (time between the injections). Several optical diagnostics were performed successively. The mixing process is studied by normalized Laser Induced Exciplex Fluorescence giving access to the vapor fuel concentration fields. In addition, the flow fields both inside and outside the jets are characterized by Particle Imaging Velocimetry. The combustion process is studied by simultaneous 355 Laser Induced Fluorescence (LIF) and OH LIF, providing simultaneous information about the localization of formaldehyde, poly-aromatic hydrocarbons (PAH) and hydroxides. Finally, soot concentration is measured by the Laser Extinction Method. The analysis of the mixing processes shows that, in the case of a short dwell time, the velocity fields associated with each injection interact, leading to an increase of the mixing rate at the head of the second injection. This interaction and the resulting effects on mixing are reduced if the dwell time is increased. The analysis of the combustion processes shows that in the case of double injections, the ignition of the second injection is promoted by the entrainment of high temperature gases originating from the combustion of the first injection. As a consequence, while for the

conditions studied no soot are formed during the combustion of the first injection, the combustion of the second injection is more fuel rich and therefore forms PAH and soot. Also, for the operating conditions studied, it was found that when the dwell time is increased, the extension of the combustion of the first injection leads to the presence of low temperature intermediates closer to the injector nozzle at the timing of the second injection. As a result, those higher temperature gases are entrained faster in the second jet, provoking faster ignition, and stabilization of the flame closer to the nozzle. Consequently the combustion is more fuel-rich, therefore forming higher concentrations of PAH and soot compared to the shorter dwell time.

INTRODUCTION

It is now well established that the new combustion modes aiming to enhance the air/fuel mixing and dilution (i.e. HCCI for Homogenous Charge Compression Ignition, PCCI for Premixed Charge Compression Ignition, LTC for Low Temperature Combustion...) are a very promising approach to reduce soot and NOx emission in automotive engines in order to meet the emission regulations. However, the implementation of those combustion modes in production engines faces significant limitations, such as combustion noise and CO/UHC emissions, that usually lead to a restriction of the use of those modes to lower loads and lower engine speeds.

In the case of Diesel combustion, among the various solutions considered to increase this operating range, recent researches have brought out the interest of multiple injection strategies to reduce the combustion

noise[1]. In fact, similar strategies are also used for conventional Diesel combustion modes when a small quantity of fuel (pilot injection) is introduced prior to the main injection in order to reduce the peak heat release rate and consequently the noise of the main combustion[2,3].

The physical phenomena involved during those multiple injection strategies are complex. A significant interaction between the mixture fields of two consecutive injections is expected, as well as a strong coupling between the combustion processes. However, those mechanisms are little known, preventing an efficient and complete optimisation of those strategies, and generating the need of detailed understanding of the physical phenomena involved.

The objective of the work presented here is to provide such an understanding, by realizing a fundamental study of the interaction of two consecutive jets issued from the same injector nozzle, in order to understand the basic mechanisms of the interaction, both in terms of mixing and combustion. The study is carried out in a constant volume vessel that provides adequate conditions in terms of optical accessibility and control of the experimental conditions. Also different optical diagnostics are used successively to investigate the mixing, aerodynamic, combustion structure and soot formation processes.

EXPERIMENTAL APPARATUS

HIGH PRESSURE CELL

The results presented here have been performed in a high-pressure, high-temperature cell which enables the study of spray behaviour under thermodynamic conditions similar to those of a Diesel engine at a specified injection timing. The major advantage of performing measurements in an optical cell is that the gas phase conditions such as air flow, temperature and pressure are more easily controlled than in an engine, whilst providing better optical access for the application of laser diagnostic techniques. The flow in the cell is essentially that induced by the spray itself.

Further details concerning the cell and its operation can be found in previous publications [4]. The injector is mounted within the top face of the cell. Five 80 mm diameter 20mm thick sapphire windows can be mounted on the other remaining faces.

Prior to performing the experiments, the gases within the cell are heated and pressurized to reproduce typical in-engine conditions by a pre-combustion technique similar to that described in [5]. The start of injection (SOI) takes place at a specified time after pre-combustion ignition. The SOI time is determined so that injection takes place when the temperature and pressure in the cell have reached the desired values. The pre-combustion gas mixture can be computed to consume a certain quantity of the oxygen initially introduced in the cell. As a result, experiments can be performed at various oxygen concentrations. For the experiments presented in this paper, "oxygen-free" corresponds to 0% oxygen during injection while "in the

presence of oxygen" corresponds to 21% oxygen by volume in the surrounding gases. An ambient density of 25kg/m^3 was used for all the tests reported in this paper.

INJECTION SYSTEM

A second generation Bosch common-rail injector was mounted in the metal top-port, directing a spray downwards into the center of the chamber. The nozzle used through all experimental investigations in this work was a single-hole nozzle with an outlet diameter of 0.2mm. The rounding rate was 5%. The nozzle drilling and the hydro grinding were performed by Posalux and Sonplass GmbH respectively.

For logistical reasons, the mixing process and the combustion process experiments were performed in two different test benches with identical equipment except for the fuel supply systems. For the velocity measurements, a CP3 Bosch pump is entrained by an electric motor. A high pressure rail was placed below the pump to avoid pressure oscillations. For the combustion measurements, a high pressure 3000bar hydro pneumatic pump was used and it is equipped downstream with a high pressure 3L vessel to deaden pressure waves. While the injection supply were different the same injector was used during all the experiments.

MEASUREMENT TECHNIQUES

Mixture visualizations

The vapor phase of the spray was visualized by Laser Induced Exciplex Fluorescence (LIEF). Details concerning the principle of the technique are available in refs. [6,7]. Usually the exciplex technique is used to distinguish the fluorescence emanating from the liquid and vapor phases. However in the present study, the investigation is focused on the vapor phase of the spray when no liquid phase is present. We still decided to use the exciplex technique although its main feature will not be used, in order to profit from the normalization method that was developed in ref [8] for the quantitative analysis of the vapor phase.

The experimental setup for fuel vapor visualization by LIEF is presented in Figure 1. TMPD tracer was added (0.5% by mass) to the fuel mixture consisting of 70% n-decane and 30% α -methyl-naphthalene, and its fluorescence was excited with a frequency-tripled Nd:YAG laser at 355nm. The laser beam is formed into a laser sheet by a cylindrical lens and a spherical lens to produce a laser sheet of width 0.5mm and height 70mm at the nozzle hole axis location. A 12bit intensified CCD camera coupled to a 80mm, f/1.4 objective was used to record fluorescence signal. In order to spectrally isolate the LIEF signal it was necessary to use appropriate optical filters (Band Pass 390nm interference filter, FWHM 10nm).

Although some degree of spectral separation can be achieved to discriminate between the liquid and vapor

phase fluorescence signals [6], in practical the signal intensity from the exciplex fluorescence corresponding to the liquid phase is generally visible when collecting the TMPD fluorescence corresponding to the vapor phase. This is due to the high fluorescence yield of exciplex fluorescence in the dense liquid spray. To avoid possible data misinterpretation, a mask was used in the presence of liquid droplet (i.e. during injection) to block the part of the laser sheet illuminating the liquid part of the spray. The position of the mask was determined by Mie scattering imaging.

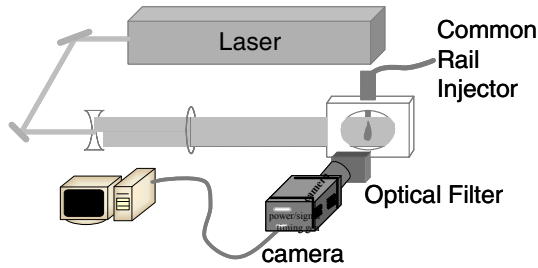


Figure 1: Experimental setup for LIEF visualizations.

The fluorescence intensity images were processed according to the following procedure: a first order numerical filter was first applied to reduce the effect of intensifier noise, then the images were corrected by the laser intensity profile, and also corrected for beam steering effects [9], finally the image intensity were normalized to obtain fuel mass concentration fields as described in ref. [8]. This normalization method takes into account the three-dimensional structure of the vapor plume and uses the known injected mass at each instant to estimate the local fuel mass concentration. A 30% accuracy was estimated for this method. An example of raw and processed images is presented Figure 2 along with the color palette that indicates the correspondence between color and fuel concentration in kg/m^3 . All the fuel concentration fields presented in this paper are using this color palette.

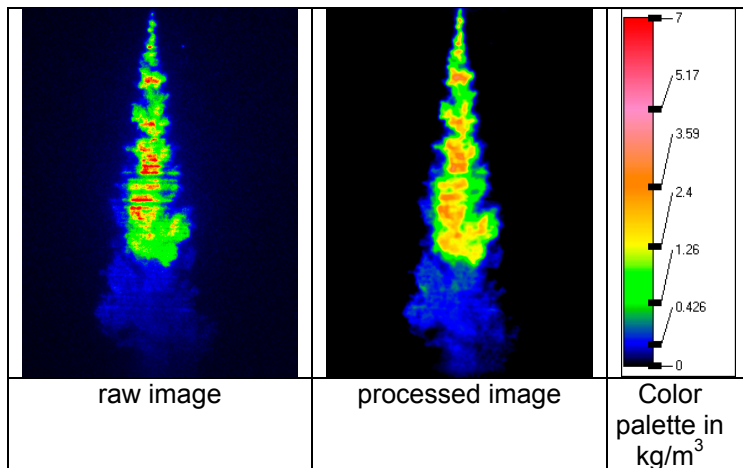


Figure 2: Example of raw LIEF image and processed fuel concentration field, and color palette in kg/m^3 .

The injected mass at a given instant is used to normalize each image. If two injections occurred at that instant the

mass taken into account is that of the two jets. Also for late timings some fuel can leave the region of investigation, inducing an error in the normalization process. The latter was estimated to be lower than 10% in the conditions studied hence lower than the estimated accuracy of the method.

Velocity measurements

The flow fields both inside and outside the jets are characterized by Particle Imaging Velocimetry (PIV). This technique is based on the Mie scattering of an incident light from particles seeded into the flow. The scattered light is collected at 90° and detected by a camera.

The stringent temperature conditions in the test cell is a major drawback for velocity measurements with the PIV technique. In non-reactive flows, the most widely used particles are liquid oils (olive oil, silicone oil,...) due to their easy seeding and their capability to trace the stream lines of the flow without disturbing it. In reactive flows, liquid oils are still efficient in fresh gases but they evaporate at flame temperatures (oil boiling points around 600K). In the present experiments, a zirconium oxide powder has been chosen to perform the experiments.

In a flow seeded particles are mainly subject to inertial forces due to the mass of the particles, and the aerodynamic forces which entrain the particles in the flow structures. The non-dimensional Stokes number St is defined as the ratio between the characteristic aerodynamic time of the particle τ_p and the characteristic time of the flow τ_F and can be reduced to :

$$S_t = \frac{\rho_p \cdot d^2}{18 \mu_{\text{gas}} \cdot \tau_F}$$

where ρ_p is the volumic mass of the particle (kg/m^3), d is the diameter of the particle (m), μ_{gas} is the dynamic viscosity of the ambient gas (Pa.s) and τ_F is the characteristic time of the flow (s). This characteristic time is estimated by the ratio of the variation of penetration and velocity for the studied jet.

For small Stokes numbers, the velocity of the particle is equal to the gas velocity, and for large Stokes numbers, the mass of the particle plays a major role. In this study, the diameter of the zirconium oxide particles are less than $5\mu\text{m}$. The volumic mass of the particle is $\rho_p=5700\text{kg/m}^3$, and the dynamic viscosity of the ambient gas is about $\mu_{\text{gas}}=38.10^{-6}\text{Pa.s}$. This leads to a small Stokes number ($S_t<1$). Therefore, the velocities of the zirconium oxide particles are expected to be mainly controlled by the aerodynamic forces of the flow.

Zirconium particles are seeded through a porous plate in a high pressure vessel. A mechanical stirrer both homogenises the particles in the seeding vessel and avoids powder to agglomerate.

The optical set-up for the PIV measurements is similar to that of Figure 1. The light source is composed of two frequency-doubled Nd:YAG lasers at 532nm. Their

repetition rate is 10Hz and the two laser beams are slightly separated in time with a delay Δt , which is adapted to the velocity range measurements. In our experiments, $\Delta t=1\mu s$ for the velocity measurements inside the jet and $\Delta t=20\mu s$ for the measurements outside the jet. The two laser beams are formed into laser sheets by a cylindrical lens ($f=50.2mm$) and a spherical lens ($f=1100mm$, $\varnothing=50mm$). The laser sheets are then aligned along with the axis of the injector. The Mie scattering signal was collected through a window perpendicular to the laser sheets by a non-intensified CCD camera (TSI, 12bit, 2048×2048) equipped with a 50mm f/1.4 Nikon lens and dedicated to PIV measurements.

The velocity fields were evaluated using an advanced commercial PIV algorithm (Insight 3G). The PIV data processing is performed on a $32\times 32pxl^2$ regular grid. In a first step, a standard PIV algorithm using multi-pass interrogation with window-shifting and Gaussian peak subpixel interpolation is used. Starting with interrogation areas of $64\times 64pxl^2$, the initially determined displacement is used as an estimate for successively smaller sub-regions. This improves the search for spatially refined correlations. The recovering rate between the interrogation areas is 50%. The spatial resolution of the velocity measurements has been evaluated at $500\mu m$.

Combustion analysis

During the injection process, the pressure increase in the cell is recorded by a QH33D AVL pressure sensor. The pressure rise induced by the jet combustion is then used to determine the heat release rate as described in ref. [10].

Combustion structure

The combustion structure was studied by simultaneous 355 and OH LIF. The principle of the technique is explained in detail in ref. [11]. The experimental set-up is presented in Figure 3. A Nd:YAG-pumped dye laser was tuned to excite the Q1(6) line of the A-X(1,0) transition of ground state OH near 282.93nm. This transition was chosen since it gives satisfactory signal over noise levels with this apparatus. The laser energy was 20mJ. A second frequency tripled Nd-YAG laser was used to generate a 250mJ laser beam at 355nm in order to excite the formaldehyde and PAH fluorescences. The two beams were then formed into laser sheets by two $f=300mm$ cylindrical UV lenses. The two sheets were then aligned with a semi-reflecting plate, before being both focused in the center of the cell by a $f=1000mm$ UV lens. The two resulting coplanar laser sheets entered the cell through a sapphire window. The two laser sheets had similar size of $70mm\times 1mm$.

The OH and 355 LIF signals were collected through two opposing sapphire windows placed perpendicularly to the laser sheet, by two intensified CDD cameras (Princeton instrument, 16 bit, 512×512) equipped with 45mm f/1.8 UV lenses. The intensifier gates were set to 50ns, and maximum camera gains were used in all the

images presented in the paper. For the OH LIF collection, a two element optical filter pack was employed to isolate the OH fluorescence signal from laser elastic scattering, fluorescence from PAH and LII from soot. The optical filter pack consisted of a 312nm unblocked band pass filter and a 358nm short wave-pass blocked filter [12]. For the 355 LIF collection a set of high pass 435nm and low pass 500nm optical filters was used to similarly isolate the formaldehyde and PAH fluorescences. The efficiency of the optical filter pack in eliminating non OH fluorescence signals was validated by performing off line imaging (i.e. away from the resonant wavelength) at 283.775nm, as done in ref. [11]. The corresponding images are not displayed in the paper because they are black images showing no significant interference signal.

Furthermore, the two laser pulses were separated by $3\mu s$ in order to avoid any interferences between the two fluorescence excitation/collection systems. The set-up is still called simultaneous imaging although this term is not exactly true, because such a delay is too short to generate any evolution in the physical processes observed.

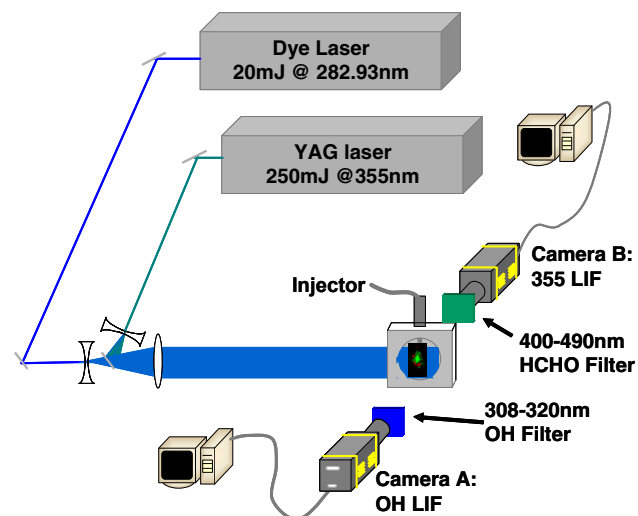


Figure 3: Experimental setup for simultaneous OH and 355 LIF imaging.

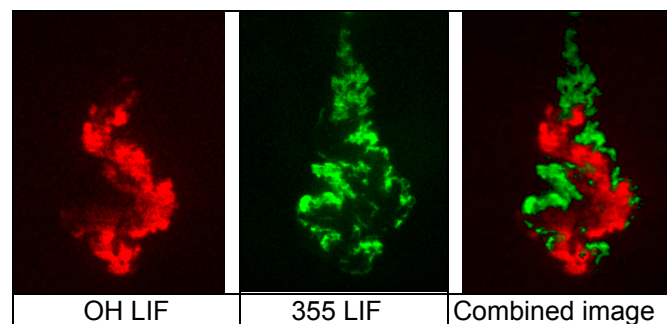


Figure 4: Example of OH LIF, 355 LIF, and combined image. OH LIF corresponds to red areas of the image, while 355 LIF corresponds to green areas.

Special care was taken to process the images in order to obtain a clear and synthetic presentation of the information. First, a first order numerical filter and a

mean filter are successively applied to reduce the intensifier noise. The first order filter is based on the selection of the minimum pixel value within a $5 \times 5 \text{pxl}^2$ area. Then the OH and 355 LIF images were combined with a specific interlacement method described in detail in ref. [11]. Examples of single LIF images and combined images are presented in Figure 4.

Soot measurements by LEM

The soot distribution in the burning jet was measured by Laser Extinction Method (LEM). This technique relies on the measurement of the attenuation of a laser beam through a soot cloud. The transmittance of the beam can be related to its optical density using a form of Beer's law [13]:

$$KL = -\ln(\tau) = -\ln(I/I_0)$$

where L is the path length through the cloud, K is the mean extinction coefficient along the path length, and τ is the transmittance, i.e., the ratio of the transmitted intensity, I , to the original beam intensity, I_0 . The extinction coefficient is related to the soot volume fraction and therefore the measurement of KL provides a quantitative information on the soot distribution in the jet.

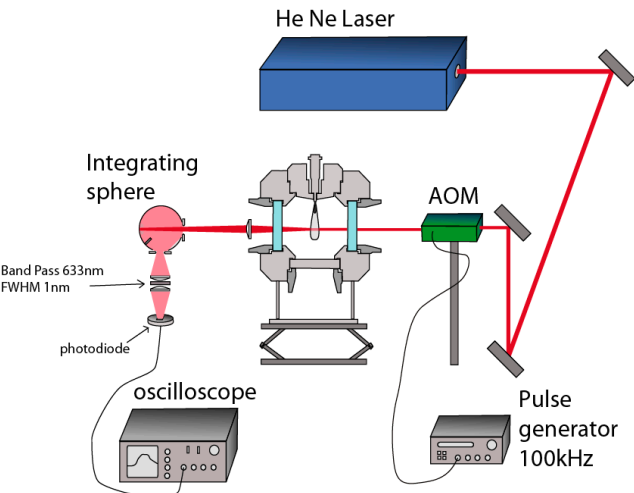


Figure 5: Experimental setup for LEM measurements.

The experimental setup is presented in Figure 5. It was designed in order to obtain reliable laser-extinction data using the solutions proposed in [14]. The laser beam of a He Ne laser was modulated in intensity at 100kHz by an acousto-optic modulator (AOM) before crossing the cell through two opposite windows. The laser beam was then converged by a cylindrical lens into a integrating sphere. The collected beam intensity exiting the sphere was collected by a photodiode after passing through a telescope consisting of two spherical lenses and a 633nm band pass filter (FWHM 1nm). The signal intensity measured by the photodiode was then acquired by a high resolution oscilloscope in order to be analyzed to provide the evolution of KL during the jet combustion at the measurement location.

OPERATING CONDITIONS

INJECTION CONDITIONS

Four injection strategies are reported in this paper and two of these are consecutive short double injections as illustrated by Table 1. The first condition (cond.1) is a single injection with a 300μs duration. The second one (cond.2) is a double injection with the first injection corresponding to the one of condition 1 and the second injection is generated shortly after (400μs). The third condition (cond.3) is also a double injection with similar injected quantities but with a longer time between the two injections (875μs). A fourth condition was added when performing the combustion process analysis (cond.4): it is a long single injection which injected mass is similar to the total mass injected during the two short double injection conditions.

Table 1: Injection conditions - duration, timings of the second injections and injected quantities. The dwell is the time between the end of the first injection and the start of the second injection. The reference time ($t=0\mu\text{s}$) is the start of the first injection.

cond.	duration (μs)			timings (μs)		Injected quantities (mg)	
	Inj. 1	dwell time	inj. 2	start inj. 2	end inj. 2	inj. 1	inj. 2
1	300	-	-	-	-	2.6	-
2	300	400	280	700	980	2.6	2.1
3	300	875	230	1175	1405	2.6	1.7
4	550	-	-	-	-	4.5	-

CELL CONDITIONS

The ambient temperature was 900K for the LIEF and PIV visualizations, with an ambient density of 25kg/m³ and an oxygen concentration of 0%.

For the simultaneous 355 and OH LIF visualizations and for the LEM measurement, the same ambient density of 25kg/m³ was used, but the oxygen concentration was 21% and the ambient temperature of the surrounding gas at the time of injection was set to 800K. This temperature was chosen to match an auto-ignition delay of about 600μs. This delay was chosen to obtain an interesting phasing between injections and combustion. Indeed as it will be seen later, with this setting the second injection of cond.2 is generated during the auto-ignition of the first injection, while for cond.3 it is generated at the end of the combustion of the first injection.

FUEL

Two different fuels were used in the present experiments.

A mixture of 70% n-decane and 30% α-methylnaphthalene was used for the mixture visualizations by LIEF. This choice was motivated by the fact that

methyl-naphthalene is used as a partner with TMPD in the Exciplex technique, see ref. [6] for more details. Dodecane 99% was used for the other measurement techniques. The choice of such a non-fluorescent fuel is particularly appropriate for the OH and 355 LIF techniques [11]. The injection pressure was 120MPa.

RESULTS

The size of the images presented in this paper is $40 \times 55 \text{ mm}^2$ for the mixture visualizations by LIEF and the velocity measurements by PIV, and $50 \times 65 \text{ mm}^2$ for the combustion images. For all cases, the jet axis is vertical and is located in the middle of the image. Fuel is injected downwards and the nozzle hole is located in the middle of the upper border of the image.

INJECTION RATE

The injection rates were determined by momentum measurements and total injected mass measurement at the same fuel temperature, injection pressure and injection durations as in the imaging experiments (see Figure 6). A piezo-electric force sensor was used to measure the spray momentum, and the injection rate was then derived under the reliable hypothesis that the injection has a characteristic top hat form.

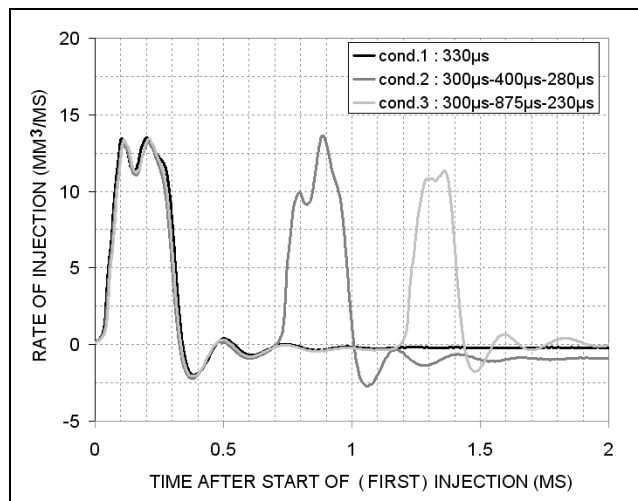


Figure 6: Injection rates for the first three conditions.

MIXTURE

The time evolution of normalized individual vapor fuel mass concentration fields for the single injection condition (cond.1) is presented in Figure 7.

Due to the slow repetition rate of the laser and the camera, the images could not be taken in the same event, and therefore the time evolution is made of images obtained in different events under "oxygen-free" conditions. The first field presented correspond to a timing of $500 \mu\text{s}$ after the start of injection, hence $200 \mu\text{s}$ after the end of injection. At this timing all the injected fuel is vaporized (the absence of liquid droplets was

verified by LIEF visualizations of the liquid). The result obtained thereafter is similar to that already observed in previous work [8]: after the end of injection, the regions of high fuel concentration located close to the nozzle mix with ambient gas quite rapidly so that fuel concentrations decrease to low values in a few hundreds of micro-seconds. This result is due to the conservation of the air entrainment dynamic after the end of injection. As a consequence, a region of low fuel concentration is rapidly formed at the tail of the jet after the end of injection, while a region of relatively high fuel concentration remains at the tip of the jet where mixing with air is significantly lower [6].

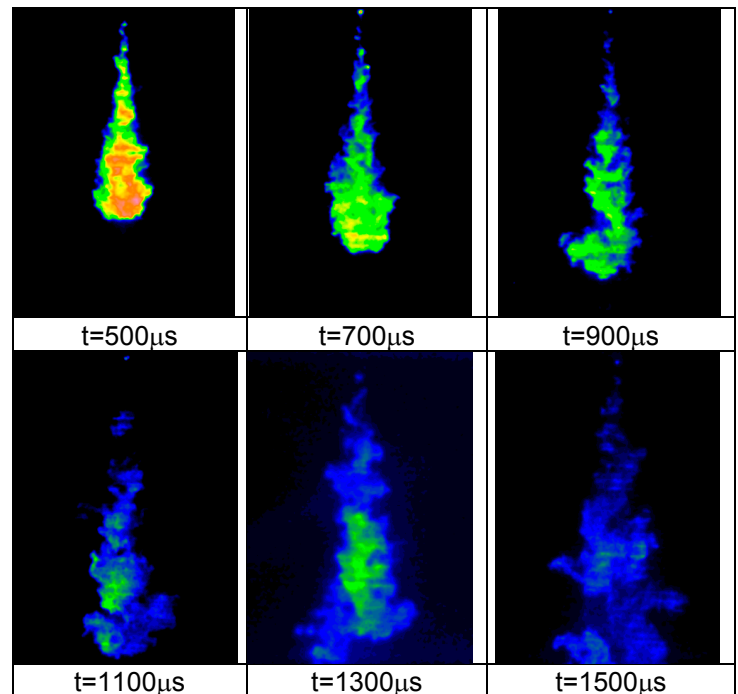


Figure 7: Evolution of individual vapor fuel mass concentration fields for cond. 1 (single injection).

Time evolution of individual fuel concentration fields for condition 2 (two injections with a dwell time of $400 \mu\text{s}$) is presented in Figure 8. The first field taken $600 \mu\text{s}$ after the start of the first injection is similar to that obtained for a single injection, since the second injection has not started yet. The fields acquired at 800 and $1000 \mu\text{s}$ were performed during the second injection, therefore with a mask blocking the laser sheet from illuminating the liquid part of the jet, hence no LIEF signal is collected from the top of the image where the liquid is located. At $1000 \mu\text{s}$, a region of high fuel concentrations corresponding to the tip of the second injection is visible at the top of the image. This second injection then further penetrates in the wake of the first injection as seen in the fields acquired at 1200 , 1400 and $1600 \mu\text{s}$. The second injection seems to follow closely the contours of the first injection, leading to the same radial extent and the same jet angle. Indeed, no regions of low fuel concentrations, corresponding to the first injection, are observed at the radial periphery of the second jet (such regions can be seen ahead of the jet tip of the second injection, but not