

Characterization of a Set of ECN Spray A Injectors: Nozzle to Nozzle Variations and Effect on Spray Characteristics

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ABSTRACT

The Engine Combustion Network (ECN) is becoming a leading group concerning the experimental and computational analysis of Engine combustion. In order to establish a coherent database for model validation, all the institutions participating to the experimental effort carry out experiments at well-defined standard conditions (in particular at Spray A conditions: 22.8kg/m³, 900K, 0% and 15% O₂) and with Diesel injectors having the same specifications. Due to the rising number of ECN participants and also to unavoidable damages, additional injectors are required. This raises the question of injector's characteristics reproducibility and of the appropriate method to introduce such new injectors in the ECN network.

In order to investigate this issue, a set of 8 new injectors with identical nominal Spray A specification were purchased and 4 of them were characterized using ECN standard diagnostics. In particular, the measurements include the nozzle hole diameter, the rate of injection, the liquid and vapor penetrations, the auto-ignition delay and the lift-off length. Variations of ambient temperature, oxygen concentration and density have also been performed.

In general the results show similar behavior to ECN standard injectors, confirming that this set of new injectors can be integrated into the pool of ECN injectors. However, discrepancies between spray characteristics were observed, although the injector specifications and the boundary conditions were sensibly the same. The sources of variations from injector to injector are analyzed in order to provide new information on the reproducibility of injectors characteristics, and improve the comparison methodology between experimental data and simulation.

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INTRODUCTION

The Engine Combustion Network (ECN) is a group of several laboratories around the world aiming at building a comprehensive experimental database for the validation of 3D models of gasoline and Diesel combustion. Standard experimental conditions have been defined ([1, 2]), that all the participating institutions have to precisely characterize and control prior to perform specific experiment. Concerning Diesel combustion investigations, the boundary conditions

corresponding to the reference Spray A are described in [Table 1](#).

The validation of the control of the boundary conditions is achieved in 2 steps:

- a direct measurement of the boundary conditions (ambient temperature and density, fuel temperature);
- a characterization of the behavior of the Diesel spray issued from one of the 5 single hole ECN injectors, supplied by Bosch, in the Spray A standard conditions, and using the

standard diagnostics defined by the network. Since the ECN injectors are similar, or to be more precise, the difference between the injectors is well known, differences in the spray behavior from one institution to another can provide information on possible differences in boundary conditions. This characterization is thus sensed to give a more precise insight into the degree of accuracy on the targeting of the boundary conditions.

Table 1. Description of ECN Spray A boundary conditions

Ambient gas temperature	900 K
Ambient gas pressure	near 6.0 MPa
Ambient gas density	22.8 kg/m ³
Ambient gas oxygen (by volume)	15% O ₂ (reacting); 0% O ₂ (non-reacting)
Ambient gas velocity	Near-quiescent, less than 1 m/s
Fuel injection pressure	150 MPa
Fuel	n-dodecane
Fuel temperature at nozzle	363 K (90°C)
Injection duration	1.5 ms
Injection mass	~3.5 mg

Previous work has been carried out to compare the experimental results obtained by different institutions. This work has been published in several papers ([2, 3, 4, 5]) and was also discussed during the two ECN workshops ([1, 6, 7]). The analysis of the results has shown that, in a first order, most of the institutions managed to reach the standard ECN conditions. But slight dispersion was observed between the results issuing from different institutions. This can be due to uncertainties in the thermodynamic boundary conditions. But an in-deep analysis has also highlighted that there are some dispersion in the injectors characteristics that can cause such differences. In spite of important efforts to precisely characterize the real specification of the ECN injectors and to relate them to the spray behavior, it is still difficult to clearly identify the causes of the dispersion in the experimental results. This question is of major importance for model validation. Indeed, differences between experimental and simulation results can have different sources that need to be understood to evaluate the models: such differences can be due to inaccuracy in the model, but also to boundary conditions uncertainties or injector to injector dispersion. Understanding the sources of these differences is therefore required to accurately determine the actual gap between the model and the experimental results. It is therefore one of the major concerns of the ECN.

A second concern is linked with the hardware availability, which may become a major issue for the ECN mechanics. Indeed, ECN is a growing community, and more injectors are required to satisfy the demand. Solutions have to be found to face this situation. In this context, IFPEN has bought a new set of 8 single hole nozzles, with the same specifications as the ECN pool, hence called hereafter "Spray A.2 injectors". These injectors have been bought in 2 pools of 4 injectors.

The first pool has a part number of 102, and the second pool has a part number of 201. For each pool, the injectors are numbered between 01 and 04. The denomination of Spray A.2 injectors is thus the following: the second injector of the first pool is for example named "Injector 102.02". Then a characterization of a selection of four of these new nozzles was carried out to compare them with the standard ECN ones in terms of nozzle hole diameter, mass flow rate, liquid length, vapor penetration, auto-ignition delay and lift off length. Since the IFPEN apparatus has already been able to reach the target Spray A standard conditions it was relevant for this institution to perform such a characterization of the new set of injectors, before stating whether these injectors can be added or not to the pool of standard ECN injectors.

In addition, the novelty of the work presented in this paper is that a set of nominally identical injectors is compared in the same apparatus, hence in similar conditions. In previous ECN characterizations, the injectors were compared in different apparatus assuming that the differences from injector to injector was negligible or could be explained. In the present study, it is relevant to assume that the boundary conditions are identical, and that the differences observed in the experimental results are mainly caused by dispersion in the injectors characteristics. This characterization will therefore help to understand how differences between nominally identical injectors can affect the main characteristics of the spray. The characterization of these Spray A.2 injectors thus meets the two concerns described earlier.

EXPERIMENTAL APPARATUS

Combustion vessel

IFPEN uses a preburn constant volume vessel to perform the spray analysis. Its characteristics are presented in [Figure 1](#) and [Table 2](#). The vessel operation has already been extensively described in previous work ([8, 2]), it is only briefly summarized here.

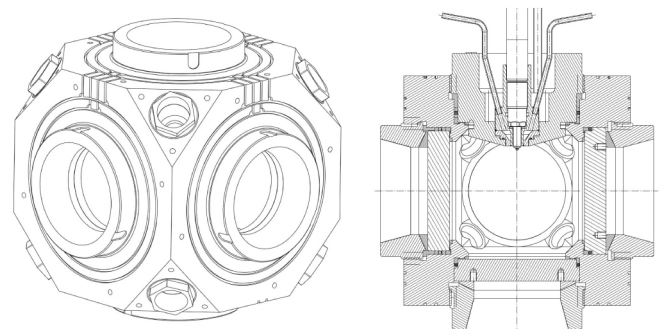


Figure 1. Global view (left) and sectional drawing (right, with an injector in vertical position) of the IFPEN vessel.

Table 2. Characteristics of the IFPEN constant volume Vessel

Internal width	125 mm
Windows diameter	80 mm
Internal volume	1400 cm ³
Ignition system	4 spark plugs, in the lower corners
Wall temperature	473 K (200°C)
Nozzle tip protrusion	3 mm

In a preburn constant volume vessel, the fuel is injected in a chamber whose pressure, density and temperature are representative of the thermodynamical conditions encountered in the combustion chamber of a real engine at the injection timing. This requires the ability to reach high temperatures and density, which is achieved by the combustion of a flammable mixture. The different steps of this process are listed below:

Filling: The vessel is sequentially filled with the flammable mixture, composed of hydrogen (H₂), acetylene (C₂H₄), nitrogen (N₂) and oxygen (O₂). The pressure and temperature of the mixture at the end of the filling process defines its density. The proportions of the gases are controlled by their partial pressures when introduced in the vessel. The proportions between N₂ and O₂ are set in order to obtain the desired O₂ fraction after the preburn event.

Preburn (or precombustion): The mixture is mixed with a stirrer during 30 seconds after the end of the filling, before the flammable mixture is ignited by 4 spark plugs located in the corners of the vessel. The combustion of the mixture generates a rapid rise of the pressure and temperature within the vessel.

Cool down: After the preburn, the pressure and temperature slowly decrease due to heat losses.

Injection: When the desired temperature is reached, the injection is triggered and the diagnostics are performed.

Two preburn vessels are available at IFPEN, with identical characteristics and control system. Previous ECN campaigns ([2, 9, 4, 3]) were carried out on the first vessel. The current experiments were carried out on the second vessel. The first vessel is therefore well characterized to reach ECN conditions, but the second one, although identical, has not been checked for ECN targeting. One additional objective of the boundary conditions characterization was therefore to verify that similar conditions are obtained in this second vessel.

Injection system

The fuel is supplied to the injector through a pipe linked to a common rail, respecting the ECN specifications ([2]). A hydro-pneumatic pump is used to generate the pressure. Its maximum capacity is 2750 bars. A set of 8 nozzles, consisting in 2 series of 4, have been bought from Bosch. These nozzles are nominally identical to the ECN standard injectors and are mounted on commercial CRI 2.16 bodies.

The nominal characteristics of these nozzles are described in Table 3. In order to differentiate the new injectors against the standard ECN ones, they are named Spray A.2 (instead of Spray A for the original ECN injectors).

Table 3. Nominal characteristics of ECN nozzles

Nozzle outlet diameter	90 μm
Nozzle shaping	Hydro-eroded
Nozzle K factor	1.5
Mini-sac volume	0.2 mm ³
Discharge coefficient C _d	0.86

Previous characterizations of standard ECN nozzles, whose results are summed-up in Table 4, have highlighted some dispersion compared to the nominal characteristics ([5]). Therefore, dispersion is also expected for the Spray A.2 injectors, which needs to be quantified.

Table 4. Summary of ECN nozzles geometry measurements ([5])

Injector #	Outlet diam. [μm]	Inlet diam. [μm]	Nozzle length [μm]	K-factor -
Nominal	90.0	105	-	1.5
Uncertainty	1.0	2	5	0.3
210675	89.4	116	1030	1.3
210677	83.7	116	1026	1.8
210678	88.6	117	1044	1.8
210679	84.1	116	1026	1.8

MEASUREMENT TECHNIQUES

The measurement techniques that have been used can be divided into two categories: characterization of the boundary conditions, and characterization of the sprays. These characterizations have been carried out in standard ECN conditions, described in Table 1.

Characterization of Boundary Conditions

All these techniques aim at providing an exhaustive characterization of all the parameters that can have an effect on the spray behavior.

Nozzle geometry

A FEI quanta 600 F Scanning Electron Microscope (SEM) has been used to define the geometry of the nozzle exit hole. The main advantage of this microscope over conventional optic devices is the increased magnification possibilities using electrons instead of light. In this case, the sample is scanned with a focused primary beam of electrons, which will interact with the specimen. Subsequently, the amount of electrons released by the interaction on a certain spot, determine the amplitude of the signal using a specific detector.

Rate of injection

The mass flow rate was measured with a commercial EMI2-EFS rate meter. The measurement principle is the following: the fuel is injected in a chamber filled with fuel. The volume of this chamber is controlled by a moving piston. A back pressure is applied to this piston. The piston displacement is measured and is used to provide the mass flow rate.

Nozzle tip temperature

The evolution of the fuel temperature during the injection event is likely to influence the spray characteristics, in particular the liquid length. Therefore it is important to be able to control its temperature. Since the measurement of the fuel temperature during the injection event is a challenge, the solution chosen by the ECN community is to measure the evolution of the temperature in the sac volume during the preburn using a dummy injector ([6, 4]), therefore without fuel and without injection. The nozzle has no orifice, and the injector is equipped with a type K thermocouple which allows to measure the temperature in the sac volume, at different distances from the bottom of the sac (Figure 2).

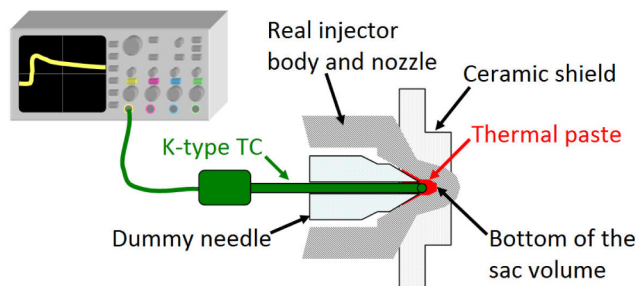


Figure 2. Scheme of the setup used to measure the temperature in the sac volume with a dummy injector

In order to limit the temperature rise within the sac volume, ECN injectors are shielded with a ceramic cover (or ceramic shield) that insulates the nozzle and reduces the heat transfers between the hot gases within the vessel and the injector. The dummy injector is also mounted with the same ceramic shield (Figure 2).

Ambient temperature

After the preburn event, during the cool down process, the temperature and the density are not homogeneous in the vessel. Average values (named as “bulk”) are thus different from local values, especially in the center of the vessel (named as “core”). The standard conditions specified by ECN are for the core values, which are thus the ones that must be controlled.

The two vessels are permanently equipped with pressure sensors. This means that for all preburn events, the bulk temperature T_{bulk} (i.e the average temperature) in the vessel can be computed through the perfect gas law:

$$T_{bulk} = \frac{P_{vessel}}{Z.r.\rho_{bulk}} \quad (1.1)$$

where Z and r are respectively the compressibility factor (needs to be taken into account for real gas effects) and the gas constant of the mixture, P_{vessel} is the pressure measured by the sensor, and ρ_{bulk} is the average density in the vessel, controlled during the filling of the vessel. Because of the thermal boundary layer generated by heat transfers at the walls of the vessel, the core temperature T_{core} (in the center of the vessel) is higher than the bulk temperature T_{bulk} . Consequently, since the pressure P_{vessel} is homogeneous in the vessel, there is also a density gradient. Based on the perfect gas law, we have:

$$\rho_{core}.T_{core} = \rho_{bulk}.T_{bulk} \quad (1.2)$$

Since there are 2 unknown values, T_{core} and ρ_{core} , another relation is required. This is the aim of the ambient temperature measurements. The temperature within the vessel is measured with a type K 50 μ m diameter thermocouple. The temperature is measured in the center of the vessel. The raw temperature measured by the thermocouple is corrected to take into account the effects of the radiations, convection, and thermocouple inertia ([2]). The characterizations of the temperature distribution within the first IFPEN vessel have been carried out previously ([2, 9]). The temperature distribution in the second vessel, used in the present work, is supposed to be identical.

Spray Characterization

After the characterization of the boundary conditions, the second step aims at characterizing the behavior of the spray for the different injectors.

Liquid length

Several techniques can be used to measure the liquid penetration of a spray. Pickett et al. ([10]) have performed an exhaustive study of these different techniques. Among them, the ECN participants agreed to chose the Diffuser Back-Illumination (DBI) technique, because it is simple, quantitative and robust. The advantages and limitations of this DBI method are detailed in ([10, 9]) but can be summarized as: 1) it is quite simple to set up, 2) it is self-calibrated 3) it enables robust quantitative comparisons between results of several institutions, 4) it suffers from beam-steering, which limits the measurement precision for the actual liquid length. But this limitation is not a major issue if the objective is to compare results obtained between institutions, since in this case the comparison of the signal drop off is enough. The corresponding setup is presented in Figure 3.

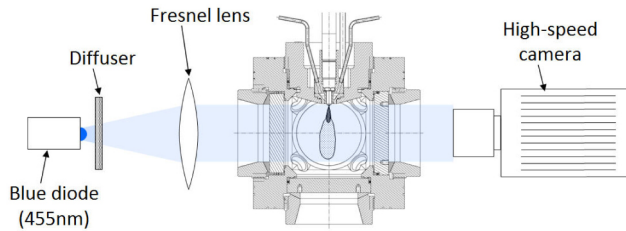


Figure 3. Diffuser back-illumination setup

The light source is a blue diode at 455nm. In order to obtain an illumination as homogeneous as possible, an engineered diffuser is placed just in front of the diode. A Fresnel lens is then used to collimate the light rays. The signal is collected by a high-speed Photron SA1 camera, whose frame rate is 120kHz, equipped with a 50mm f/1.2 lens and a 8mm extension ring. The resolution of the images is 320×112pxls, and the spatial scale is 88.5μm/pxl. The resulting field of view is about 28×10mm². An example of the images obtained with such a technique is shown in Figure 4, together with the corresponding time averaged image during the injection event.

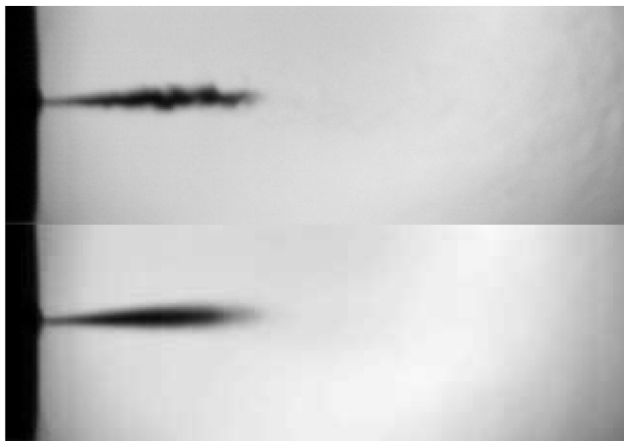


Figure 4. Example of an image obtained with the DBI setup (top), and the corresponding time averaged image during the steady state of the injection event (bottom)

The processing method consists in converting the time averaged intensity images into extinction images. The extinction is noted τ and is computed as:

$$\tau = -\ln\left(\frac{I}{I_0}\right) \quad (1.3)$$

where I is the image intensity, and I_0 is the reference intensity (i.e. without any extinction). Then, the extinction profile along the spray axis is analyzed. An example of such a profile is displayed in Figure 5.

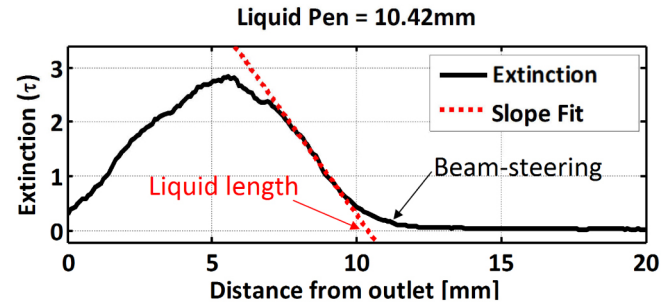


Figure 5. Example of the processing of extinction images

Near the liquid core tip, beam-steering is significant, and thus the extinction value is the consequence of both the light extinction and the beam-steering. The profile in this region can therefore not be taken into account to compute the liquid length. Instead, the slope of the decay of the extinction profile is computed, and the liquid length is defined as its intersection with the x-axis.

Vapor penetration

Measurement of the vapor penetration is performed with a Schlieren setup, detailed in Figure 6.

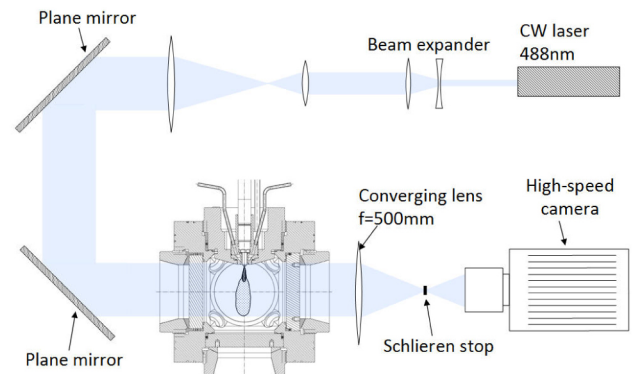


Figure 6. Schlieren setup

The light source is a continuous wave laser at 488nm. The beam issuing from the laser is shaped into a larger parallel beam of 8cm diameter. The light is collected with a high-speed Photron SA1 camera, equipped with a 100mm f/2.8 lens and a 8mm extension ring. The resolution of the images is 640×240pxls, and the spatial scale is 117μm/mm. The resulting field of view is 7.5cm × 2.8cm. The frame rate is 30kHz. The spatial filter (Schlieren stop) is a cutoff disk whose diameter is 1.2cm, that blocks non-deviated rays. As a result the sprays appear in white on a dark background (dark field Schlieren). This setup has been chosen against the bright field setup because it gave the best contrast for the spray images. An example of such an image is given in Figure 7.

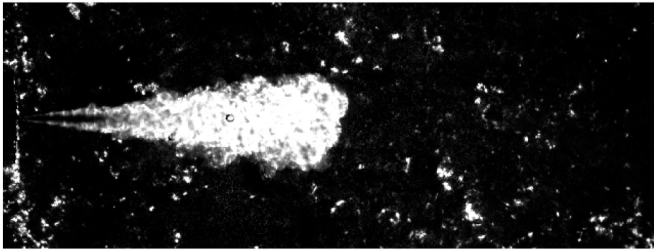


Figure 7. Example of an image obtained with the Schlieren setup

The processing of such images consist of detecting the border of the spray and then taking the maximum value of vapor penetration at each timing.

Auto-ignition

The detection of the auto-ignition was performed by two different methods. The first one is based on direct visualization of the flame chemiluminescence with a high-speed camera. For this method, a trade-off has to be made between time resolution and sensitivity. Indeed, the higher the frame rate, the higher the precision of the auto-ignition delay determination. But at the same time, increasing the frame rate will decrease the integration time of the camera, and thus decrease the amount of light collected, hence the auto-ignition detection sensitivity. In the present study, a compromise frame rate of 40kHz was chosen, corresponding to a 25 μ s precision on the auto-ignition delay measurement. To optimize the sensitivity of the setup to chemiluminescence, the camera was equipped with a high aperture 50mm f/1.2 lens. Such a setup is sensitive enough to detect the light emission from the cool flame. The difficulty of the image analysis is therefore to identify the contribution of high-temperature chemiluminescence versus cool flame. The methodology used in the present work is based on an intensity threshold: below this threshold, the light emission was considered as being due to the cool flame; above, it is attributed to the high temperature combustion. This methodology is described in [3]. In our study, we obtained 8-bits images for which the leveling-off value representing high temperature chemiluminescence was approximately 100 counts. The threshold for auto-ignition delay detection was thus 50 counts. When the saturation of the camera sensor is observed, this is attributed to the soot incandescence. Based on this distinctions, we have considered the following analysis of the intensity I :

- background noise: $0 \leq I \leq 2$ counts
- cool flame: $3 \leq I \leq 49$ counts
- high-T combustion: $50 \leq I \leq 254$ counts
- soot: $I = 255$ counts

Figure 8 displays an example of the temporal evolution of the high speed combustion images. Cool flame zones are

displayed in blue, high-temperature combustion in orange, and soot in red. When the high-temperature combustion has started, the blue zones can no longer be considered as cool flame. The auto-ignition delay is defined as the time when the first occurrence of high-temperature chemiluminescence (orange) is observed ($t=0$ corresponds to the effective start of injection).

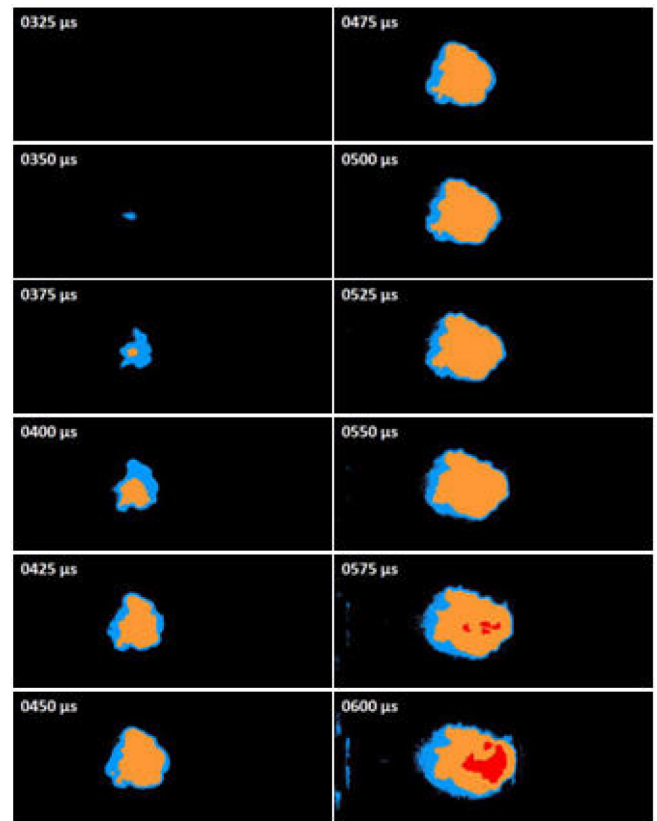


Figure 8. Temporal evolution of the combustion. Images obtained by direct visualisation of the combustion. Injector is on the left side and injects towards the right. Spray A conditions: 22.8kg/m³, 900K, 15%O₂ (%vol.).

The second method used to measure auto-ignition delay is based on the analysis of the pressure evolution in the vessel. The latter was equipped with an additional pressure sensor to the one used to record the preburn event, dedicated exclusively to the measurement of the pressure rise during the combustion of the injected fuel. This pressure sensor is located in one of the lower corners of the vessel, thus requiring to remove one of the 4 spark plugs. An example of the signal obtained with this pressure sensor is presented in Figure 9, showing that the signal is quite smooth before the start of combustion, and becomes more noisy afterwards. The processing consists in detecting the time of the first peak of the noise (red circle on Figure 9 - bottom)