

# Study of Low Soot or Soot-Free Leaner Lifted Flame Combustion in a Light Duty Optical Engine

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## ABSTRACT

Previous experimental data obtained in constant volume combustion vessels have shown that soot-free diffusive flames can be achieved in a Diesel spray if the equivalence ratio at the flame lift-off location is below 2. The so-called Leaner Lifted-Flame Combustion (LLFC) strategy is a promising approach to limit the levels of in-cylinder soot produced in Diesel engines. However, implementing such strategies in light-duty engines is not straightforward due to the effects of charge confinement, non-steady boundary conditions and spray-spray interactions compared to the simplified configuration of a free-jet in a constant-volume combustion vessel. The present study aims at trying to gain a better understanding of the requirements in terms of injector and engine settings in order to reach the LLFC regime in a light-duty engine.

Experiments were performed on a 0.5L single-cylinder optical engine. Various injector nozzle geometries were investigated, offering variations in the number of holes (7 to 14), in hole diameter (63µm to 123µm) and in nozzle mass flow rate (240ml/min to 672ml/min). The impact of variations in engine operating conditions was also studied, in terms of EGR rate (0% to 65%), injection pressure (800bar to 1600bar), swirl (1 and 1.5), and boost pressure (1bar to 2.2bar). Engine-out soot emissions were measured with a smoke meter. The combustion process was characterized using a high-speed camera which collected the broadband emission of incandescent soot. An intensified camera recorded once per cycle OH\* chemiluminescence at 310nm.

The results shows how in-cylinder soot formation is affected by the parametric variations. In particular, for low levels of EGR, the rate of soot formation is very high and mainly driven by in-cylinder thermodynamic conditions. For high EGR levels(e.g. > 65%) the reaction rates are too low to enable soot formation, even if the thermodynamic conditions are favorable.

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## INTRODUCTION

Reducing engine-out soot emission of Diesel engines is an alternative to complex after-treatment systems in order to comply with pollutant emissions legislation. But conventional Diesel combustion systems are facing the soot-NOx trade-off issue, which associates an increase of NOx emissions to a decrease of soot emissions. Therefore, several advanced combustion strategies have been studied in recent years in order to reduce soot emissions without increasing NOx ones. These advanced combustion strategies are based on achieving Low Temperature Combustion (LTC) conditions. The objective is to obtain a more homogeneous mixture which would limit i) soot production by avoiding zones with equivalence ratios higher than 1, and ii) NOx formation through lower combustion temperatures [1]. However, these new combustion concepts show several limitations, the main ones being:

- The control of combustion phasing is more difficult, since it is not only dependent upon fuel injection, but also by the chemical kinetics reactions, which in turn are strongly affected by any variation in thermodynamic conditions;

- The maximum achievable load is limited, mainly because higher combustion speeds are achieved compared with conventional combustion strategies, since the entire mixture can auto-ignite in a short period of time;
- Higher CO and HC emissions because of higher dilution and lower temperature.

In order to limit those drawbacks, several variations of LTC systems have been developed in the last 10 to 15 years, leading to several denominations (HCCI, PCCI, RCCI,...) [2, 3, 4, 5, 6, 7]. But, even if significant progress has been achieved, none of these strategies have been able until now to eliminate completely those drawbacks. This is why an interesting path to follow is to improve conventional Diesel combustion in order to limit soot formation. This type of combustion has been referred to as Leaner Lifted Flame Combustion (LLFC) in [8]. It is based on the now well-known influence of equivalence ratio in the lift-off region on soot production. In particular, it has been shown that an equivalence ratio lower than 2 at lift-off results in a non-sooting flame [9, 10, 11, 12, 13]. Such combustion conditions have been achieved in combustion vessels, where the sprays are in an

environment without any effects of confinement and with well-controlled boundary conditions. Many parameters can be tuned in order to reduce equivalence ratio at lift-off ( $\Phi_{LOL}$ ). A reduced equivalence ratio at lift-off can be achieved mainly by two ways:

- Increasing lift-off length (LOL): this can be obtained by decreasing the ambient temperature, decreasing the ambient density, increasing the injection pressure [14]
- Increasing air entrainment: this can be obtained by decreasing orifice diameter, increasing ambient density.

By varying these parameters, many studies have tried to achieve this combustion regime in an engine. Polonowski et al. [8] used three different injectors (2-, 6- and 10-holes, 110 $\mu$ m orifice diameter) on an optical heavy-duty engine. High injection pressures were also employed, ranging from 140MPa to 240MPa. The results revealed that LLFC was achievable for the 2-hole injector, but was not sustainable with the 6- and 10-holes injectors. The reason was a progressive decrease of the lift-off length (and thus an increase of the equivalence ratio in the lift-off region) caused by re-entrainment of hot combustion products, and by the existence of spray-spray interactions. Chartier et al [15] and Aronsson et al. [16] also studied LLFC in an optical heavy-duty engine, with 3-hole injectors and orifice diameters in the range of 100 $\mu$ m and 140 $\mu$ m. Injection pressures were also high, varying from 150MPa to 250MPa. Their results showed that i) cycle-to-cycle variations had a significant impact on equivalence ratio at lift-off ( $\Phi_{LOL}$ ) [16] and ii) engine-out soot was not necessarily correlated with  $\Phi_{LOL}$  [16].

This literature review shows that there is a need for investigations on LLFC in light-duty engines, with injectors that are more representative of next generation orifice size and orifice number. In the present study, the objective was to attempt to achieve LLFC regimes in an engine environment. Current, production series and next generation injectors were compared, for a variety of operating conditions. The aim was to gain a better understanding of which parameters have an impact on LLFC in a light-duty engine.

## EXPERIMENTAL APPARATUS

### Optical Engine

An optical-access single cylinder engine with a 0,5 liter displacement was used in this study. The engine had a 85mm bore and 88mm stroke and is thus representative of a light duty direct-injection (DI) 4-stroke Diesel engine. The swirl can be varied between 1.0 and 1.5 by adjusting the position of a flap located within the tangential intake port. The engine was equipped with an intake heater allowing preheating of the fresh intake air, and with a simulated EGR (nitrogen) circuit to target representative oxygen concentrations of the intake air compared to standard metal engines.. A schematic view of this engine is presented in Figure 1, and the general engine characteristics are listed in Table 1. This engine could be equipped in several optical configurations to enable the application of laser based diagnostics for in-situ measurements:

- Fully/partially optical crown: this corresponds to the upper part of the liner, in which transparent windows can be installed. This

optical crown can also be fully optical made of sapphire in order to have a full optical access to the upper part of the combustion chamber.

- Replacement of one of the two exhaust valves by a window providing a view from the cylinder head down into the combustion chamber;
- Optical piston: an optical bowl window is used;
- Optical liner: the entire liner is transparent.

Because of the optical windows, optical engines can behave in a different manner compared to standard metal engines. These differences have been studied in [17].

Table 1. Characteristics of the IFPEN single-cylinder Diesel optical engine.

| Characteristics                   | Value             |
|-----------------------------------|-------------------|
| Number of cylinders               | 1                 |
| Cycle                             | 4-Stroke          |
| Number of intake valves           | 2                 |
| Number of exhaust valves          | 1                 |
| Combustion chamber                | Flat optical bowl |
| Cylinder head type                | Flat              |
| Displacement                      | 500cc             |
| Bore                              | 85 mm             |
| Stroke                            | 88 mm             |
| Connecting Rod                    | 145 mm            |
| Geometrical compression ratio     | 15:1              |
| Swirl range at Bottom Dead Center | 1.0 – 1.5         |

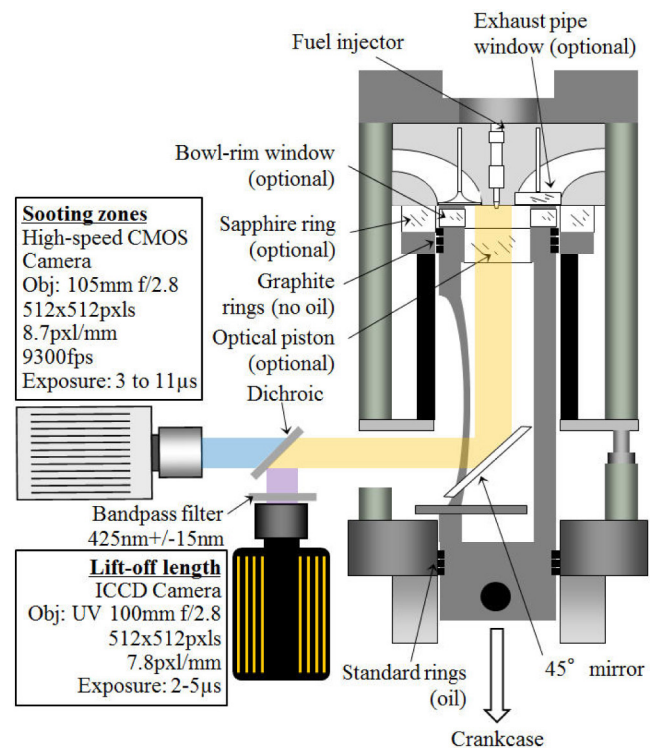


Figure 1. Schematic diagram of the IFPEN Diesel optical engine.

## Fuel Injection Systems

The engine is equipped with a common rail fuel injection system (Bosch CP2) capable of supplying fuel at nominal rail pressures up to 1600 bar. Several Delphi solenoid injectors DF11.5 were used in this study, with various number of holes and orifices diameters. Their characteristics are listed in Table 2. The fuel used in the present study was standard European Diesel fuel whose principal physical properties are presented in Table 3.

Table 2. Injector specifications. In bold red police, characteristics that are similar for different injectors.

| Injector name | Number of holes | Orifice diameter [ $\mu$ m] | Mass flow rate [ml/min] | Included angle [ $^{\circ}$ ] |
|---------------|-----------------|-----------------------------|-------------------------|-------------------------------|
| 7/123         | <b>7</b>        | 123                         | 672                     | 160                           |
| 7/88          | <b>7</b>        | 88                          | <b>340</b>              | 160                           |
| 10/75         | <b>10</b>       | 75                          | <b>340</b>              | 160                           |
| 14/63         | 14              | <b>63</b>                   | <b>340</b>              | 160                           |
| 10/63         | <b>10</b>       | <b>63</b>                   | 240                     | 160                           |

Table 3. Properties of the Diesel used in this study.

|                                   |                    |               |
|-----------------------------------|--------------------|---------------|
| Density @ 20°C                    | kg/m <sup>3</sup>  | 831           |
| Viscosity @ 40°C                  | mm <sup>2</sup> /s | 2.5           |
| Cetane number (ISO 5165-98)       | -                  | 52.1          |
| %C - %H - %O                      | %mass              | 86.1-13.3-0.6 |
| Lower Heating Value (ASTM D 4868) | MJ/kg              | 42.94         |

## Operating Conditions

One engine operating point was studied, corresponding to a low speed (1500rpm) and partial load (6bar IMEP) condition. The settings corresponding to the reference operating point (with injector 7/88) are listed in Table 4.

Table 4. Settings of the reference operating point.

|                  |      |      |
|------------------|------|------|
| Speed            | rpm  | 1500 |
| CA50             | cad  | 367  |
| IMEP             | bar  | 6    |
| Eq. Ratio        | -    | 0.22 |
| P <sub>2</sub>   | bar  | 2.2  |
| T <sub>2</sub>   | degC | 52   |
| SSE <sup>1</sup> | cad  | 353  |
| DSE <sup>1</sup> | ms   | 0.78 |
| Q <sub>air</sub> | kg/h | 50   |
| Prail            | bar  | 1200 |
| EGR rate         | %    | 0    |

Around this reference point, mono-parametric variations of rail pressure, intake manifold pressure, swirl and charge dilution were performed in order to understand their effect on lift-off length and soot production. They are summarized in Table 5. Two types of variations can be defined:

- variations of operating conditions with the same injector;
- variations of injectors with the same operating conditions.

It must be noted that simulated (N<sub>2</sub>) EGR was used in this engine. Therefore, the values of EGR rates given in the next sections of the paper are computed based on the N<sub>2</sub> rate and the equivalence ratio. The corresponding EGR rate is the one that would give the same O<sub>2</sub> concentration in the intake air. The correspondence between EGR rate, N<sub>2</sub> rate and equivalence ratio is summarized in Figure 2

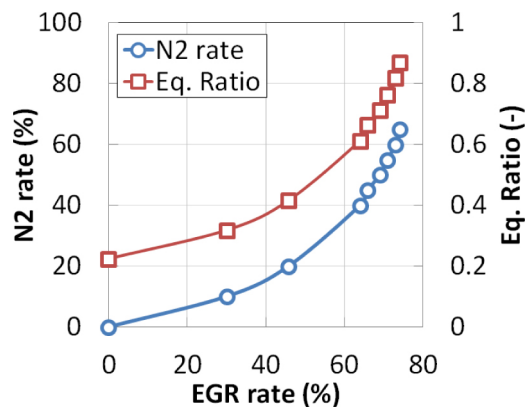


Figure 2. Evolution of N2 rate and equivalence ratio as a function of EGR rate.

The following rules have been applied during the variations of operating conditions:

- **constant fuel injected quantity**: during a variation of dilution, the mass of injected fuel is maintained constant. This implies a variation of equivalence ratio, but allows to isolate the impact of combustion processes on soot measured in the exhaust line;
- **constant equivalence ratio**: during variations of intake manifold pressure, the injected quantity is adapted in order to have the same equivalence ratio;
- **constant CA50**: combustion phasing is kept constant for all the operating points, which means that the Start of Solenoid Energizing (SSE) is adapted for each operating point.

Due to the optical windows, the thermal loading of the engine differs from that of the corresponding full metal engine. In order to limit this thermal loading and be more representative of a full metal engine, a skip fire strategy is employed: each fired cycle is followed by 5 non-fired (motored) cycles. This affects the measurements of equivalence ratio and smoke at the exhaust, since there is additional dilution cause by the motored cycles. During another experimental campaign on this optical engine (but with different operating conditions, injector and compression ratio), smoke and equivalence ratio have been measured for different skip fire strategies. The results are presented in Figure 3, which shows the dependence of smoke and equivalence ratio measured in the exhaust line to the number of skip-fired cycles. It must be noted that in Figure 2 and everywhere else in the paper, when values of equivalence are mentioned, they refer to the equivalence ratio that would be measured without skip firing.

Table 5. List of all the variations of operating conditions for all the injectors tested. Point #1 is the reference operating condition.

| Injector | Swirl | Prail | P2  | Dilution                    | Op. point # |
|----------|-------|-------|-----|-----------------------------|-------------|
| -        | -     | MPa   | bar | %EGR                        | -           |
| 7/88     | 1     | 120   | 2.2 | 0/30/45.8/64/66/69/71/73/74 | 1           |
|          | 1.5   | 120   | 2.2 | 0/45.8/66                   | 2           |
|          | 1     | 80    | 2.2 | 0/66                        | 3           |
|          | 1     | 160   | 2.2 | 0/66                        | 4           |
|          | 1     | 120   | 1   | 0/37.6/55                   | 5           |
|          | 1     | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 6           |
| 7/123    | 1     | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 7           |
| 10/75    | 1     | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 8           |
|          | 1.5   | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 9           |
| 10/63    | 1     | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 10          |
| 14/63    | 1     | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 11          |
|          | 1.5   | 120   | 1.6 | 0/39.1/56.4/63.2/68.4       | 12          |

Light collection is done through a 45° mirror placed under the optical flat piston (window size: 46mm), and then the signals are separated by a dichroic.

A high-speed Photron SA1 CMOS camera, equipped with a 105mm f/2.8 lens, collects the natural blackbody emission from soot, at 9300fps (1 image each crank-angle degree at 1500rpm). A high-pass spectral filtering is performed by the beam splitter. The resolution of the image is 512×512 pixels, corresponding to 59×59mm (8.7mm/pixel). Depending on the operating conditions, the exposure varies from 3 to 11μs, in order to avoid sensor saturation by soot luminosity. 40 images are recorded per cycle, and 30 repetitions are performed in order to allow statistical analysis of the results.

A Pimax 3 ICCD camera, equipped with a 100mm f/2.8 UV lens and a bandpass filter (@ 425nm, 30nm width), collects the chemiluminescence from the flame. Only 1 image per cycle is recorded, but the trigger of the camera is varied in order to be able to reconstruct a complete cycle. During 60 consecutive cycles, the triggering of the camera is increased by 1 crankangle degree (CAD) every 5 cycles. This is repeated 5 times, which gives 25 images per crank-angle. This allows to have an average image on 25 injections events, on a 12 CAD range, with the first image being recorded few CAD after SSE in order to start acquisition when combustion begins. The resolution of the camera is 512×512 pixels, corresponding to a field of view of 66×66mm (7.8 pixel/mm).

Usually, the best marker of lift-off is the chemiluminescence of the OH radical at 310nm [18, 19], since it is present in high-temperature stoichiometric flames. However, in our case, the collected emission at 310nm was very low and therefore we decided to collect emission at 425nm (+/-15nm), near the CH radical emission at 431nm [19], which was more intense. This is sensed to give higher values of lift-off length [18] but in this study, this is mainly the variations in lift-off length that are analyzed than its absolute values.

### Processing Methodologies

The images acquired by both cameras are first ensemble averaged (30 repetitions for soot emission, 25 repetitions for lift-off length). The processing methodologies described below are applied to those ensemble averaged images.

### Lift-Off Length

An example of a processed 425nm-chemiluminescence image is presented in Figure 4. For each spray, two intensity profiles are analyzed, corresponding to the two lines forming a 5° angle with the spray axis. The intensities are normalized and lift-off length is defined as the first axial distance where the normalized intensity is above a defined threshold. This is an adaptation of the methodology described in [18] for 310nm-chemiluminescence images (looking at the OH radical). Then, the lift-off length is the average value on all the sprays. The choice of the threshold value has an influence on the measured lift-off length: a higher threshold will lead to a higher measured LOL. In order to assess this effect, lift-off lengths are computed for 10%, 20% and 30% threshold values (denoted LOL 10%, LOL 20% and LOL 30%). LOL 10% and LOL 20% are

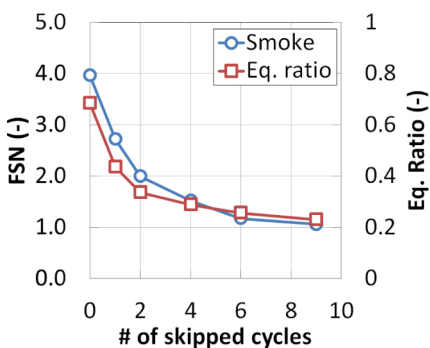


Figure 3. Dependence of smoke and equivalence ratio to the number of skipped cycles (0 skipped cycle corresponds to a combustion every cycle, 9 skipped cycle corresponds to one combustion followed by 9 motored cycles).

### Optical Setup

Two different chemiluminescence imaging setups are used simultaneously for this study. Natural broadband emission from soot is used to obtain the spatial location of the flame, and to estimate the amount of soot produced by the combustion. Narrowband emission from high-temperature radicals helps estimate the lift-off length.

then normalized by LOL 30%. The results are presented in Figure 5. It can be seen that LOL 20% is about 8% lower than LOL 30%, and LOL 10% is approx. 18% lower than LOL 30%.

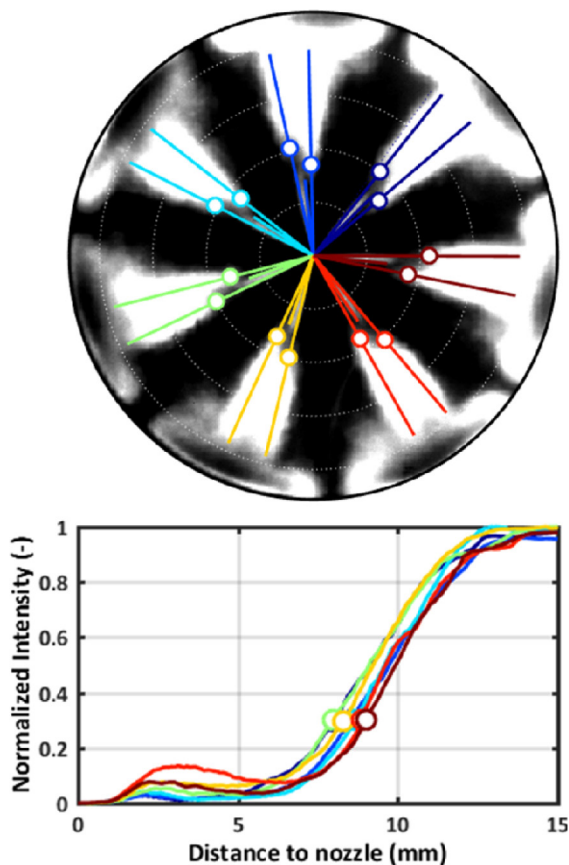


Figure 4. Top: Example of a 425nm-chemiluminescence image at 363CAD (SSE is 353CAD), for operating point #1 (see Table 5) at 0% EGR. The colored lines are on both sides of the jets axis, forming a 5° angle with it. The circles represent the computed lift-off position. Bottom: Normalized intensity profiles along the colored lines, circles are the computed lift-off length (30% of the maximum intensity).

This effect is significant and will affect the estimation of equivalence ratio at lift-off length ( $\Phi_{LOL}$ ). In the following, the value of 30% has been chosen for the threshold because it was more reliable than 10% and 20%, and therefore could be applied universally to all the conditions tested in this study. Two limitations have to be noted in our case. The first one is that we are collecting light at a higher wavelength (425nm +/- 15nm), which should result in a slightly higher lift-off length [18]. However, this assertion must be mitigated by recent results presented at the 4<sup>th</sup> ECN Workshop [20], in Topic 7. Signals from the blue channel of a high-speed color camera ( $\lambda > 400\text{nm}$ ) and from a high-speed intensified camera collecting at 310nm were compared, for a three hole injector in a heavy-duty optical engine. The flame structures and measured lift-off lengths were very similar, showing that collecting signal at a higher wavelength than 310nm can result in similar lift-off length. The second limitation, as appears in Figure 4, is that the CCD sensor can be saturated on some images. This means that the maximum intensity should be higher, and also the threshold used to compute the lift-off length. Therefore, saturation leads to shorter values of lift-off length.

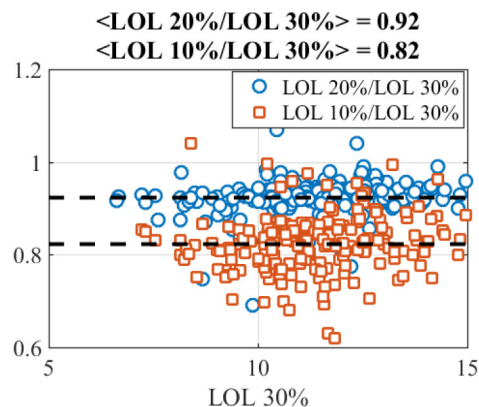


Figure 5. Effect of the threshold used for lift-off detection on the measured lift-off length. X-axis is the LOL computed with a 30% threshold (LOL 30%). Y-axis is the LOL computed with 20% threshold (LOL 20%, blue circles) and 10% threshold (LOL 10%, red squares) normalized by LOL 30%. The title gives the average values of the ratios.

### Soot Quantity

Natural broadband emission images are processed in order to estimate the amount of soot produced by the flames. The methodology is close to the one described in [8]. The images are corrected for the exposure time and the f-stop of the lens, since they were not recorded with the same settings in order to avoid saturation of the sensor. Then, for each image, the background noise is defined as all the pixels that have an intensity lower than 7% of the maximum intensity of the images. This threshold was chosen by successive tries on several images. The combustion zones are the region where intensity is higher than the background noise. Three different indicators are then computed: the maximum intensity of the combustion zones, the total intensity (sum of all the pixels located in the combustion zone), and the average intensity (total intensity divided by the number of pixels in the combustion zones). Soot luminosity is dependent on the soot volume fraction and on their temperature. Here, we would like to eliminate the effect of temperature to only keep the dependence of intensity to soot volume fraction  $f_v$ . The methodology followed to estimate  $f_v$  is presented in Figure 6. Based on the Stefan-Boltzmann law, the power radiated by a blackbody is proportional to the fourth power of its thermodynamic temperature. Assuming that soot follow this law, the collected intensity has to be normalized by  $T^4$  (where T is the soot temperature) in order to eliminate the effect of temperature. Soot temperature is assumed to be equal to the adiabatic flame temperature. This latter is computed for stoichiometric mixtures, knowing the reactants temperature and the EGR rate. The reactants temperature is estimated considering that fresh gases are undergoing an isentropic compression due to the expansion of the burnt gases. Following this methodology, the collected light can be transposed into an estimation of soot volume fraction.

### Heat Release Rate (HRR)

Acquisition of the pressure trace was performed at 0.1 crank-angle degree intervals. The HRR is computed on the average pressure trace. This computation takes into account heat transfers, estimated using the Woschni model and the real thermodynamic properties of the gases (JANAF polynoms). It is performed with the 2D-Magnum 3.0 Amesim™ software and the IFE-Engine library developed at IFPEN.