

Analysis of Combustion Process in Cold Operation with a Low Compression Ratio Diesel Engine

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ABSTRACT

Future emissions standards for passenger cars require a reduction of NO_x (nitrogen oxide) and CO_2 (carbon dioxide) emissions of Diesel engines. One of the ways to reach this challenge while keeping other emissions under control (CO: carbon monoxide, HC: unburned hydrocarbons and particulates) is to reduce the volumetric compression ratio (CR). Nevertheless complications appear with this CR reduction, notably during very cold operation: start and idle. These complications justify to intensify the work in this area.

Investigations were led on a real 4 cylinder Diesel 13.7:1 CR engine, using complementary tools: experimental tests, in-cylinder visualizations and CFD (Computational Fluid Dynamics) calculations. In previous papers, the way the Main combustion takes place according to Pilot combustion behavior was highlighted.

This paper, presents an in depth study of mixture preparation and the subsequent combustion process.

Using Laser illumination techniques, in-cylinder visualizations highlight - even at low engine speed during cranking operation - the existence of swirl motion moving the fuel being vaporized inside the chamber. In these conditions, visualizations and computations show that the vicinity of the glow plug and one injector spray leads to a combination of adequate temperature and air/fuel ratio and so to the combustion initiation. CFD calculations also point out that the “stair shape” evolution of heat release can come from a progressive propagation of combustion from one spray to another.

Using the available tools, it appears also that some troubles encountered in cold idle can be attributed to inadequate engine control.

The tools developed (experimental tests, in-cylinder visualizations, and calculations) have proven quite effective and complementary capabilities in order to investigate and to understand the physical phenomena encountered during cold operation (start and idle). Even if correlations are not always easy to establish between these phenomena and engine performance: speed stability or smoke opacity, these tools will allow to progress in this area and to further improve engine behavior and emissions.

INTRODUCTION

A large part of the European passenger cars is powered by a Diesel engine. Indeed this kind of engine is appreciated thanks to its high efficiency and induced low CO_2 emissions.

Nevertheless, future regulations require a further reduction of CO_2 and pollutants emissions (notably NO_x) while keeping other emissions under control (CO, HC and particulates). The use of new combustion modes coupled with a strong downsizing allows to reach this target, but that also implies reducing the volumetric compression ratio (CR) [1 and 2]. Nonetheless, specific attention must be paid in order to avoid damaging the engine behavior in cold operation (start and idle) at extremely low temperatures (-10°C and below) when applying this CR reduction [3].

Investigations have been carried out at IFP for several years, on a real 4 cylinder Diesel engine with a very low CR: 13.7:1 (see [3, 4 and 5]), and this paper offers a synthesis of main results obtained in this area. Various tools have been developed in order to analyze the engine behavior and the combustion development: cold test cell, optical set up (allowing in-cylinder high speed visualizations), and CFD calculations. These tools allow to investigate and to understand the main parameters affecting cold operation.

The analysis highlights the different stages leading to fuel combustion in such severe conditions: mixture preparation (with an analysis of swirl number and rail pressure impact), combustion initiation (with impact of hardware and injection settings analysis) and combustion development. The inefficient and non conventional combustions are also investigated and finally, combustion development and engine behavior are compared in order, if possible, to establish correlation links.

EXPERIMENTAL SET UP

The experimental set-up is quite similar to that described in a previous paper [5].

TEST CELL AND MEASURING EQUIPEMENT

The temperature can be controlled from -30°C to $+30^{\circ}\text{C}$ in the test cell. Classical engine data such as: temperature and pressure for most of the engine's fluids, air/fuel ratio, voltage and intensity or ECU parameters can be recorded during the tests. Opacity is also measured in the exhaust line with the help of AVL 439 opacimeter. An optical shaft encoder is implemented in order to record in-cylinder pressure and signals needed for visualization (as explained in the description of the “Optical Measurement System”).

TEST TEMPERATURE

With basic instrumentation, tests can be operated at very low temperature. For example, the start ability of the engine with low CR has been investigated till -25°C as exposed later.

When using more sensitive instrumentation (e.g. fast camera described later), tests are operated at higher temperature: -5°C . This temperature is not extremely low, but considering the low CR of the engine used for this work (13.7:1), in-cylinder temperature at TDC (Top Dead Center) is close to that obtained at ambient temperature of -20°C with a state of the art CR (16:1).

ENGINE TEST PROCEDURES

The standard test procedure is the following: the engine's electric starter - powered by the 12V battery - is used to crank the engine at the end of the preglowing phase. After start, the engine is running in idle for about 2min, to characterize idle behavior under such conditions.

MAIN CRITERIA EVALUATED IN COLD OPERATION

In order to qualify engine behavior in cold operation, three main criteria are considered in this paper:

- Start delay: defined as the time period between the moment when the starter is switched on and the moment when the

engine has really started: i.e. when ECU “Start Bit” appears, which means that the engine has just reached “idle phase”,

- Exhaust Gases Opacity: the signal delivered by AVL 439 opacimeter is commonly illustrated versus time on the figures and it is averaged during different periods in cold operation,
- Engine Speed Stability: at each acquisition step (frequency is 100Hz), the standard deviation is averaged on sliding interval (for 1 sec. i.e. 100 samples) before being drawn (see “std_dev. (rpm)”) or averaged for a longer period

TEST ENGINE, COMBUSTION SYSTEM DESIGN AND BASIC SETTINGS

The engine tests are performed on a four cylinders PSA DW10 ATED4 engine with the characteristics specified in Table 1.

Table 1. Engine specifications

Engine Reference	PSA DW10 TED4
Engine Type	4 cylinders, turbocharged, intercooler, direct injection
Cylinder Head	4 valves / cylinder
Bore x Stroke	85 mm x 88 mm
Displacement	1998 cm3
Fuel Injection System	Common Rail Bosch CRI 1, injector with 6 holes, spray angle: 144° , static hydraulic flow: 347cm3/ 30s/10MPa
Compression Ratio	13,7:1 (nominal 18:1)
Glow plug	Ceramic Glow Plug

The compression ratio (CR) is reduced from nominal value: 18:1 to lower one: 13.7:1, by enlarging the piston bowl volume, while maintaining the squish area and the general shape of the nominal bowl.

With a first adaptation of injection settings and hardware configuration (glow plugs definition: temperature and relative position according to injector spray), start delay was reduced as to obtain, till -25°C , the same value as the reference engine with conventional CR [3]. However, engine behavior appears to be poor during idle phase, just after start. For an in depth study of cold operation, using sensitive instrumentation, adaptations were necessary, in order to get an acceptable engine behavior during start and idle at -5°C . This work is not detailed in the present paper, but the main settings are resumed in Table 2 and an illustration of engine behavior is presented in Figure 1. It can be considered as a baseline for the rest of the work.

<table 2 here>

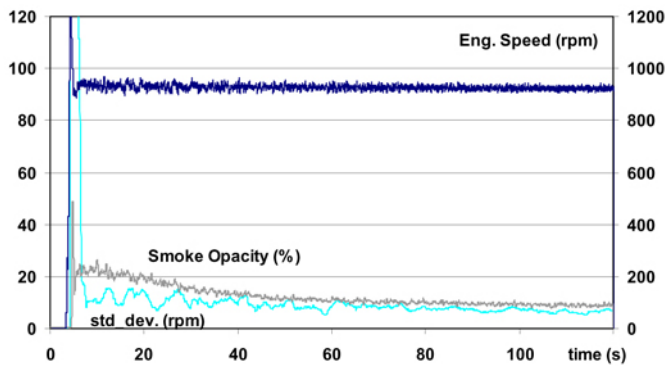


Figure 1. Base line engine behavior during cold start then idle at -5°C

OPTICAL SET UP

An optical set up close to that used in previous experiments [5] is installed for these experiments.

ENGINE OPTICAL PATHS AND CONFIGURATION

The engine is equipped with a modified cylinder head to allow two optical paths on cylinder 4 (see Figure 2). The piston lip is machined to allow visualization even at TDC position, as illustrated in Figure 3. An optical fiber with a quartz tip and an endoscope are installed into the paths in order to respectively light up and visualize phenomena in the cylinder chamber.

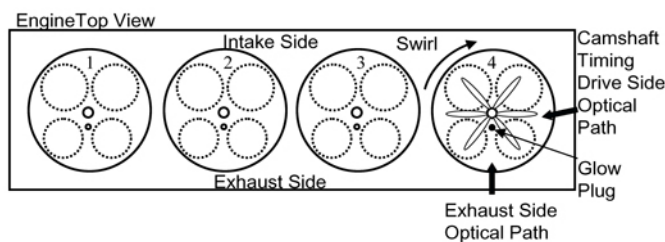


Figure 2. Engine design with optical paths on cylinder 4

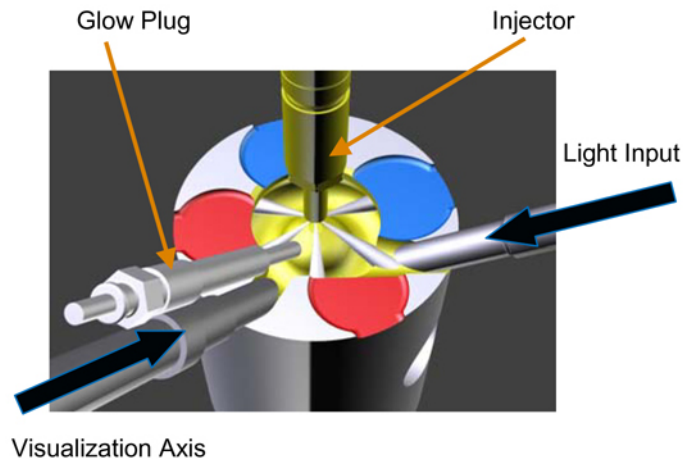


Figure 3. CAD picture of optical paths towards combustion chamber

In the images acquired according to “Visualization Axis” and presented below (e.g. Figure 6), the light comes into the chamber from the right of the image, the injector is behind the glow plug in the center of the image and the bowl dome area is visible at the bottom.

OPTICAL MEASUREMENT SYSTEM

The measurement system is made up of a high speed intensified camera connected to the endoscope with a flexible optical multifiber (see Figure 4). To improve the combustion chamber illumination especially during injection, a specific light source: a high frequency 10kHz pulsed Laser is implemented. Its high energy pulses (10mJ/100ns) combined with shorter camera exposure time allow to visualize high speed phenomena like injection in the combustion chamber. In return, the increase of light amount in the cylinder generates optical noise. This noise was reduced, but due to in-cylinder reflections, light spots appear on the top right side of some images (see Figure 10).

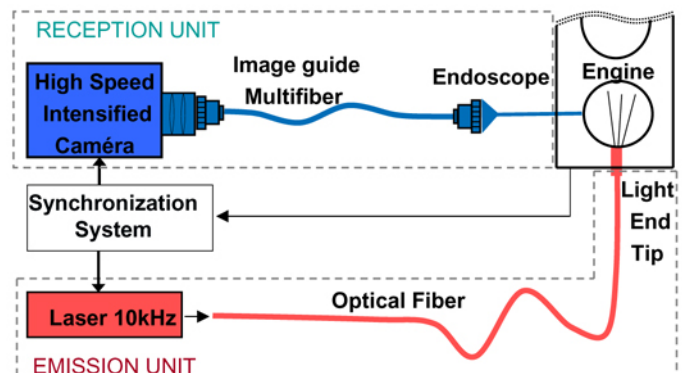


Figure 4. Optical measurement configuration

The optical set up is adapted for cold start tests at negative temperature: -5°C . To protect the intensified camera, a

specific heated and regulated box is used in order to put this equipment directly in the test cell.

An electronic system is adapted to synchronize both the camera and the Laser with the engine rotation. This set up allows to record up to 16 images/cycle, with a minimal interval close to 0.3CAD at idle speed (maximum speed is 1 megapictures/s), and with a 640×511 frame resolution. All the engine cycles can be recorded during starting phase (at low engine speed), but due to the backup procedure, only one every two cycles at maximum, is recorded during idle phase.

IMAGE ACQUISITION PROCEDURE AND PROCESSING

With the help of the system allowing to synchronize the image sequences acquisition and the Laser illumination pulses with the engine rotation, the operator can set up the image acquisition timings before the test. During the test, a high rate acquisition system (0.1°CA) records analog data for each engine cycle: cylinder pressure, injection command pulses, camera trigs, etc.

Figure 5 presents an overview of cold start test with optical measurements. Engine speed and cylinder pressures are illustrated, whereas black marks (named “image cycles”) indicate engine cycles where image sequences are acquired. For this test, they have been acquired during the first and the second cycles of cylinder 4, and then every three cycles during the idle phase.

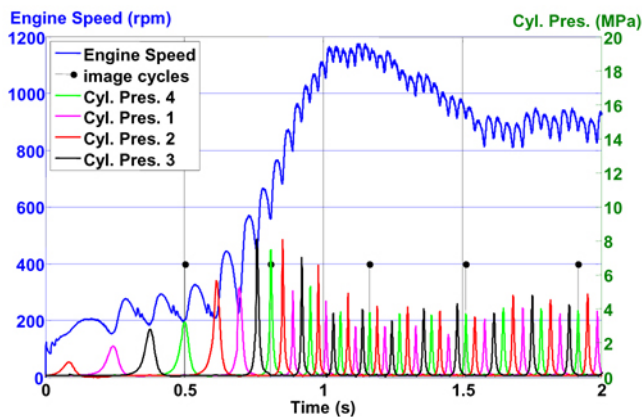


Figure 5. Overview of cold start with engine speed, cyl. pressures and engine cycles with image acquisition

During post-processing, the apparent “net heat-release” rate is calculated as proposed by [6]. The heat transfer losses are deliberately not considered (see [5]), due to the difficulty to estimate them during transient cold start with varying in-cylinder conditions.

Figure 6 illustrates the data obtained during the first fired cycle on cylinder 4 of a cold start test. The injection pulses,

cylinder pressure and calculated heat release rate are presented in the graph. Events like the fall of heat release rate during the Main injection phase can be noted. The “Image Trigs” corresponding to the real image acquisition crank angles are also shown here. This gives the link between local phenomena observed on images - with Pilot injection and combustion illustrations on the left of the graph, and Main injection and combustion illustrations on the right of the graph -, and the evolution of global parameters inside the chamber (illustrated in the graph).

<figure 6 here>

This image sequence allows to observe phenomena like the combustion of the Pilot injection (331 - 334°CA) and the combustion of the Main injection (347 - 352°CA) linked to the heat release signal. In this way, in cylinder visualization allows to affirm that the Pilot injection is partially but really burning while this combustion does not appear clearly on the cylinder pressure evolution neither on heat release. Taking into account the benefic effect of Pilot injection combustion on Main injection combustion, it seems very interesting to take advantage of visualization in order to analyze Pilot combustion and interaction with Main combustion, as it will be shown later. Similar acquisition and post processing procedures are used for each test.

NUMERICAL SET UP

INTRODUCTION

The aim of the numerical part of the study is to bring information in order to help to understand the physical mechanisms occurring during the starting phase of a Diesel engine with low CR in low temperature conditions.

DESCRIPTION OF THE 3D CFD CODE

The three-dimensional simulations were performed using IFP-C3D code [7], which solves the unsteady equations of a chemically reactive mixture of gases, coupled with the equations for a multi-component vaporizing fuel spray. This 3D CFD parallel (Open MP or MPI) code solves the Navier-Stokes equations using an ALE-extended (Arbitrary Lagrangian Eulerian, see [8], [9] and [10] for more details concerning this model and its validation) finite volume method on conformal unstructured hexahedral meshes. The code uses the well known time splitting decomposition, while the temporal integration scheme is largely implicit.

For turbulent combustion, the 3-Zone Extended Coherent Flame Model (ECFM3Z) is used [11]. The auto-ignition prediction and the influence of chemistry on reaction rates are provided by the TKI (Tabulated Kinetics of Ignition) auto-ignition model [12]. To obtain a realistic spray modeling during the injector needle motion, the Transient Injection Conditions (TIC) model [13] is used. All those different

physical models were already described in [3], [4] and [5]. The main specificities are recalled below.

Fuel Injection Modeling

The spray of the injector is discretized in parcels (set of droplets with same characteristics). Turbulence model is k-ε and the Wave/FIPA model [14] is used to model the evaporation and the break-up. For cold start purpose, the spray/wall interactions must be taken into account ([15] and [16]). Hence, the wetting of walls by the injected fuel (liquid film) is modeled using an in-house Lagrangian model based on the O'Rourke and Amsden [17], [18] model for the formation, the evaporation and the splashing. This model was improved using the work of Xu and Han [19], [20]. The modeling of liquid film dynamics takes into account the spray impact, the surface motions and the gas evolutions in the vicinity of the film.

Ignition and Combustion Modeling

For compression ignited internal combustion engines, the combustion modeling relies on the combination of two models. The ECFM-3Z (a complete description is available in [11]) model describes the turbulent mixing in each mesh cell and provides the local thermo dynamical conditions and species concentrations to the TKI auto-ignition model (more extensively described in [12] and [21]). The latest model represents the chemical kinetics related to the combustion process. After the start of combustion, the representation of the turbulent mixing by the ECFM3Z model allows to define the local conditions in order to well represent the combustion process.

Blow-by and crevice volumes Modeling

The piston shape was specifically designed in order to obtain a combustion chamber with a nominal compression ratio of 13.7:1. In order to “take into account” the important blow-by flow rate existing during the first engine cycles in cold start conditions, a blow-by model is used.

This model is a subpart of a more complex one devoted to the representation of unburnt hydrocarbon due to the existence of cavities such as cylinder head gasket and piston ring pack.

One of the interests of this model consists in the fact that the crevice volumes are not integrated in the computational domain and do not have to be meshed. The flow rate between the computational domain and the external capacity depends on the in-cylinder pressure and is directly linked to the geometry of the ring pack and the cylinder head gasket. This model allows to take into account 5 cavities for the description of ring pack and cylinder head gasket (see Figure 7). Several parameters allow to describe the geometry of the crevices and to tune the leak flow rate towards the sump.

It was observed [5] that increasing only the blow-by value is not enough to get the right pressure losses near the TDC especially when the fuel is injected. Indeed, the use of a model which can take into account the crevices allowing a temporary maximization of the mass losses seems to be necessary (at least in the present case) to get a realistic representation of the in-cylinder pressure evolution. The different parameters of IFP-C3D's blow-by model were set on the basis of the real geometry of the piston, the ring pack and the cylinder head gasket. The values were slightly adapted (some tenth of mm) in order to adjust the leak flow rate towards the external capacities of storage.

The heights of cavities 2 and 3 (ring grooves) are the parameters used to adjust the leak flow rate (real blow-by phenomenon). The values of the different parameters are given in Table 3.

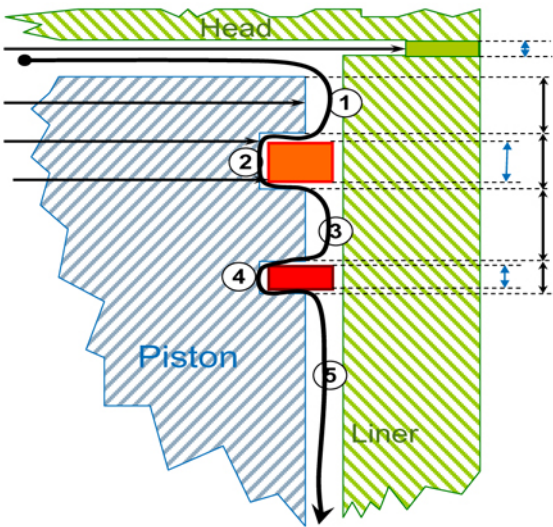


Figure 7. Schematic representation of the blow-by model

Table 3. Values of parameters used in blow-by model

Parameter	Value
Gasket Thickness	1 mm
Gasket diameter	88,2mm (104% bore)
In ring diameter	77,8mm
Ring thickness	3,2mm/2,0mm
Ring width	3,6mm
Height of 4 first cavities	7,1 / 3,255 / 8 / 2,055mm
Piston diameters	84,5 / 77,2mm
Sump pressure	0.1 MPa

Computational assumptions

The present study is based on the experience acquired during previous studies [3], [4] and [5]. The main effort was put on the representativity of the computational model. Indeed the previous studies on the same topic show that during the first

engine cycle in cold start conditions the temperature distribution in the combustion chamber is very heterogeneous. Here the whole experimental combustion chamber is modeled with the main geometrical singularities (notably the recesses due to optical access).

Computational Domain

For cold start consideration the glow plug has to be taken into account. Moreover, in order to improve the representativity of the numerical model, the whole combustion chamber corresponding to the experimental optical one is modeled. As a consequence, one of the two specific recesses (the main one) which were machined in the piston for experimental optical visualization (endoscope and light entrance) is taken into account in the computations.

The computational mesh is shown in Figure 8. The glow plug is represented by a specific wall with a given target temperature (about 1400°C similarly to the experimental temperature) that can be varied.

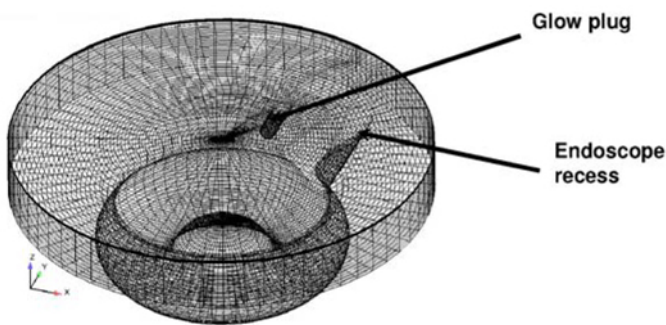


Figure 8. Mesh of the computational domain

The meshes are realized using ICEM-CFD Hexa. Their size varies between about 227300 (start of computation at intake valve closing) and 150500 hexas (during injection and start of combustion). The changes in mesh size are performed using remapping algorithm.

Initial and Boundary Conditions

The computation starts at the Intake Valve Closing (IVC) of the first engine cycle. The initial pressure is fixed at 0.1 MPa and the initial swirl motion is set at 2.3 (nominal value). Specifications of the injector are the same as for engine tests (Bosch CRI 1 with spray angle equal to 144° and 6 holes). The instantaneous flow rate is fitted on experimental data. The injected fuel is a single component model possessing almost the same characteristics as experimental fuel. Computations were performed with same injected mass as experiments.

When the computation starts at IVC, the chamber is supposed to be filled with pure fresh air at the external temperature (-5°C). The piston, cylinder head and cylinder liner

temperatures are similar. Only the walls of the glow plug are heated at a nominal target temperature equal to 1400°C.

During the modeled first cycle, the engine is supposed to be cranked by the starter at 266 rpm (mean revolution velocity measured during experimental first engine cycle) and this speed is supposed to be constant even if a combustion occurs.

COMBUSTION PROCESS IN COLD OPERATION

In this part, the different stages leading to fuel combustion are studied: air/fuel mixture preparation (with an analysis of swirl number and rail pressure impact), combustion initiation (with impact of hardware and injection settings analysis) and combustion development. The inefficient and non conventional combustions are also investigated and to finish, combustion development and engine behavior are compared in order, if possible, to establish correlation links.

AIR FUEL MIXTURE PREPARATION

The following analysis is divided in several parts in order to describe successively the behavior of the fuel (injection, vaporization), then the behavior of the air and finally the behavior of the mixture.

Fuel behavior

Tests are operated during cranking at -5°C, 240 to 280 rpm, Rail Pressure: 30MPa, with only a Pilot injection (injected quantity: 10mm3/strk, SOI Pilot: 22CAD BTDC -Before Top Dead Center- and nominal swirl) without pre glowing and so without combustion. That allows to analyze the injection process. Figure 9, similar to that described before, shows that only a little fall of heat release rate appears during the injection phase, due to the partial vaporization of fuel.

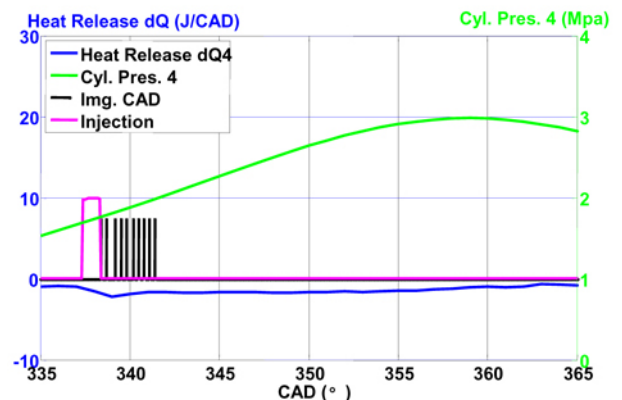


Figure 9. Development of engine cycle during cranking, with only one Pilot Injection and without pre glowing neither combustion

The [Figure 10](#) presents images obtained during this cycle. In spite of the adaptation of Laser illumination process (see “Optical set up” description), light reflection remains on the right of the images.

The images located on the top concern the injection phase. Two injector sprays appear clearly on the left and on the right of the first image (338.3CAD). At this moment, the spray coming close to the visualization axis or injector/glow plug axis (named “middle spray”) is hidden by the glow plug, but it appears in the second image. In the third image (339.9CAD) the sprays are no longer visible just at the outlet of the injector because the injection is finished, but they are moving forward in the chamber without any deviation. This means that liquid fuel is not influenced by the swirl and CFD calculations will confirm this tendency later.

In the images located on the bottom (~341 CAD and after), luminous intensity of the sprays decreases. The visualization techniques used here do not allow to see the gas inside the combustion chamber, but the decrease of the luminous intensity can be linked to fuel vaporization. The “cloud” of fuel being vaporized is then deviated by the swirl on the left near 341.4 CAD. That is a precious information: the swirl motion is really influencing aerodynamic phenomena and mixture preparation even at low engine speed: *i.e.* during cranking.

<[figure 10](#) here>

Air behavior

[Figures 11](#) generated from CFD calculation results and obtained during cranking (first engine cycle) shows that the air heated by the glow plug is carried downstream by the rotational swirl motion. In addition to visualization results, this proves that the swirl motion cannot be neglected even at such a low engine speed (during cranking). Indeed, the aerodynamic motion impacts directly the temperature stratification phenomenon occurring in the combustion chamber.

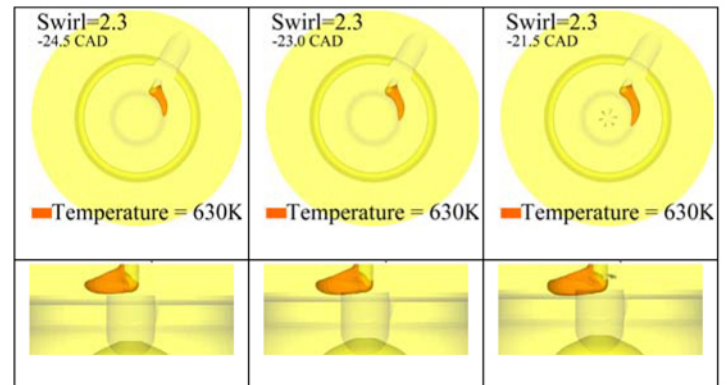


Figure 11. 3D visualizations from computations showing the evolution of the hot wake downstream the glow plug at nominal swirl level, just before Pilot injection

In fact, the temperature of the hot area downstream the glow plug is not high enough to induce the auto ignition: previous results [4] show the existence of a threshold below which no auto ignition can occur. Nevertheless, thanks to the proximity with the glow plug itself, the spray upstream is partially vaporized, providing gaseous fuel and allowing the combustion initiation at the glow plug's wall [5], which is the favored location where the required level of temperature can be found. Moreover, the temperature of the hot area downstream the glow plug helps in the vaporization of the sprays located downstream, and so in combustion development.

Impact of main parameters

Impact of swirl number increase on air behavior

Three different levels of swirl motion were computed. In addition to the nominal one (2.3) a very low (0.22) and a high (4.6) level were tested. The influence of this variation on the hot wake downstream the glow plug can be observed in [Figure 12](#) and it will be discussed later (when analysing results of [Table 4](#)).