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Cold Operation with Optical and Numerical Investigations on a Low Compression Ratio Diesel Engine

B. Walter, H. Perrin, J. P. Dumas and O. Laget
IFP

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ABSTRACT

With a high thermal efficiency and low CO2 (carbon dioxide) emissions, Diesel engines become leader of transport market. However, the exhaust-gas legislation evolution leads to a drastic reduction of NOx (nitrogen oxide) standards with very low particulate, HC (unburned hydrocarbons) and CO (carbon monoxide) emissions, while combustion noise and fuel consumption must be kept under control. The reduction of the volumetric compression ratio (CR) is a key factor to reach this challenge, but it is today limited by the capabilities to provide acceptable performances during very cold operation: start and idle below -10°C.

This paper focuses on the understanding of the main parameter's impacts on cold operation. Effects of parameters like hardware configuration and calibration optimization are investigated on a real 4 cylinder Diesel 14:1 CR engine, with a combination of specific advanced tools. In-cylinder high speed visualizations allow to observe locally injection and combustion processes and to complete the standard combustion analysis operated from heat release which is a more global approach. Moreover, the CFD (Computational Fluid Dynamics) calculation, which combines the local and global approaches, is really helpful when phenomena take place out of the visualization area.

Very local phenomena specific to cold operation as combustion of the spray close to the glow plug, or combustion in the hot burned gases coming from the Pilot injection combustion have been highlighted. Thus, concerning hardware configuration, glow plug and spray interaction appears to be the first order parameter and glow plug temperature shows a great influence on cold idle. Concerning calibration, the use of Pilot injection improves significantly cold operation (especially opacity and engine speed stability), by deeply modifying the fuel and temperature stratification in the combustion chamber.

INTRODUCTION

Progresses in technologies such as turbo-charging, injection systems, EGR capabilities and combustion systems have turned the Diesel engine as a vital component of the transport sector. Indeed, its performances in terms of efficiency and therefore CO2 emissions are about 25% less than a traditional gasoline engine of equivalent performance.

Nevertheless, the main issue for the warm operation is the trade off between full load performances (power and torque) and part load key issues notably efficiency (CO2 emissions). A strong downsizing is a clear benefit for CO2 emissions : fuel consumption reduction is approximately 9 % with a displacement reduction from 2 liters to 1.6 liters [1]. To keep same performances (specific torque and power) on downsized engines, high supercharging is generally applied and it results in higher mechanical and thermal loads [2]. To answer this problematic, the reduction of the volumetric compression ratio (CR) is a key point in order to keep identical constraints and to allow this strong downsizing. So, there is clearly a link between CO2 emissions reduction and CR reduction even if this link is not direct. Moreover, this evolution allows the use of new combustion modes on a larger load and speed range, which leads to a significant reduction of NOx raw emissions (see [3] and [4]). Nonetheless the reduction of the CR to values between 14:1 and 16:1 leads now to an other limitation (see [5]

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and [6]): behavior in cold operation (start and idle) in extreme low temperature (-10°C and below).

In a previous paper [7], consequences of the reduced CR from 17:1 to 14:1 and optimization of the injection settings in order to allow good start capabilities have been investigated with the help of CFD calculation and in-cylinder visualization.

To go deeper, this paper focuses on the understanding of the main parameter impacts on cold operation: hardware configuration (glow plug / spray interaction, glow plug type and temperature), software optimization (injection settings and especially Pilot injection). Combination of specific advanced tools is used to reach the target: experimentation on a real four cylinder engine combined with high speed visualization of injection and combustion in one cylinder (16 images per cycle), and CFD calculation with improved model.

Due to the temperature sensitivity of the instrumentation used for this study, all the tests presented hereafter have been operated at ambient temperature of 5°C. In isolation, this temperature is not extremely low, but considering the compression ratio of the engine used for this work (CR = 13.7:1), in-cylinder temperature conditions at TDC (Top Dead Center) are close to those observed at ambient temperature of -10°C with a state of the art CR (16:1).

EXPERIMENTAL SET UP

TEST CELL AND MEASURING EQUIPEMENT

The engine is installed in a cold test cell, where ambient temperature can be controlled from -30°C to +30°C. During the tests, ECU parameters acquisitions are performed by ETAS system and Inca software. Opacity is measured in the exhaust line with the help of AVL 439 opacimeter. Moreover, classical engine data are recorded such as: temperature and pressure for most of engine's fluids, Air/Fuel ratio, voltage and intensity (for starter, glow plugs….). In addition, an optical shaft encoder is implemented in order to record in cylinder pressure (with the help of four pressure transducers Kistler 6055C80) and signals needed for visualization (as explained in the description of the "Optical Measurement System").

SOAKING AND ENGINE START PROCEDURES

Before a test, the engine and the fuel tank are soaked in the cold test cell for at least 8 hours, while battery is recharged after each start test and then soaked for at least 16 hours. For this reason, three batteries are used alternatively for tests. The own electric starter of the engine – powered by the 12V battery – is used to crank the engine which is declutched for the test (start then idle). The preglowing duration depends on desired glow plugs temperature and ambient temperature, then starter is switched on at the end of this preglowing duration. After start, the engine is running at idle for about 2min in order to characterize idle behavior in such conditions. Then engine temperature and load are increased progressively in order to clean the engine before stopping it and starting a new soaking procedure. Lastly, reference tests are frequently operated in constant conditions to check the repeatability of the results.

MAIN CRITERIA EVALUATED IN COLD OPERATION

In order to qualify engine behavior in cold operation, we will consider in this paper three main criteria:

- start delay: this delay is defined as the duration between the moment when the starter is switched on and the moment when the ECU "Start Bit" signal appears, which means that "idle mode" has just been reached,
- exhaust gases opacity: the signal delivered by AVL 439 opacimeter is commonly illustrated versus time on the figures and moreover it is averaged during different periods happening 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 or averaged for a longer period as seen later….

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**.

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

Table 1: Engine specifications

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In order to reduce the compression ratio CR from nominal value: 18:1 to lower one: 13.7:1, the piston bowl volume is enlarged, keeping constant the squish area (same distance between piston and cylinder head) and the general shape of the nominal bowl (by adopting an homothetic transformation of the initial drawing) to increase the volume of the bowl, see **Figure 1**.

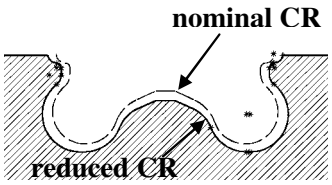


Figure 1: Combustion system (bowl technical definition), nominal CR (dotted line), reduced CR (continuous line)

To implement the optical device in cylinder 4, two holes are drilled through the cylinder head (as it will be seen in **Figure 4** and **Figure 5**). The corresponding piston is machined to facilitate optical accesses when piston is near TDC and the bowl volume is lowered for this cylinder to keep a constant CR.

This study begins with an adaptation of the engine and settings, in order to get an acceptable engine behavior during start and idle phases, at 5°C. This part of the work is not detailed in the paper, but the main settings are in **Table 2** and an illustration of engine behavior is presented in **Figure 2**. It can be considered as a base line for the rest of the work.

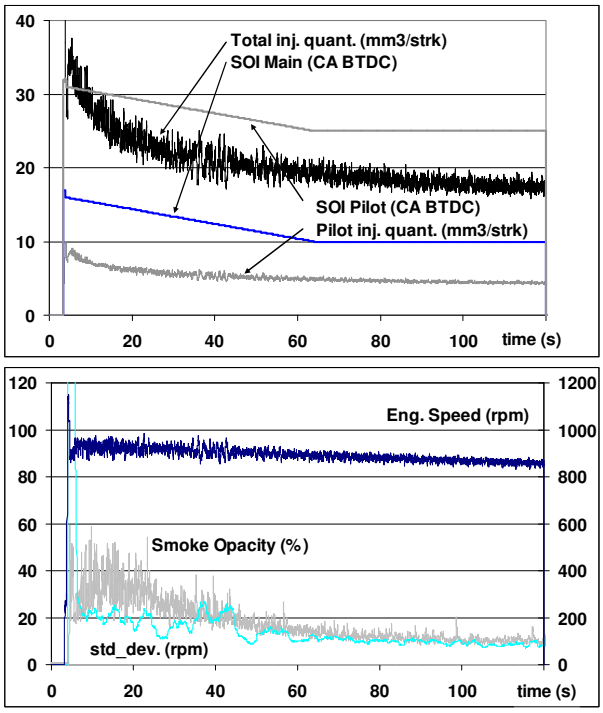


Figure 2: Engine behavior during cold start and idle with Pilot injection

Initial settings			
Spray/glow plug angle	10°	glow plug temp	1400°C
Main settings after 60s		**Main criteria after 60s**	
Rail Pressure	30 MPa	Eng. Speed	900 rpm
Total inj. quant.	19 mm3/strk	std_dev	10 rpm
Pilot inj. quant.	5 mm3/strk	Smoke opacity	15 %
SOI Main (Start of Injection Pulse)	10 CA BTDC		
SOI Pilot	25 CA BTDC		

Table 2: Engine basic settings

OPTICAL SET UP

OPTICAL MEASUREMENT SYSTEM

The optical measurement system, presented in **Figure 3**, is divided into two parts: an "emission" unit and a "reception" unit.

The "emission" unit allows to light up the engine combustion chamber especially during injection. It includes a 300W continuous light device (Xenon lamp), a 5mm optical fiber (gel fiber) and a specific 30° end-tip to introduce the light into the engine chamber. Compared to a pulsed light, this light device has been selected for its good power/volume ratio and its easy use (not synchronized).

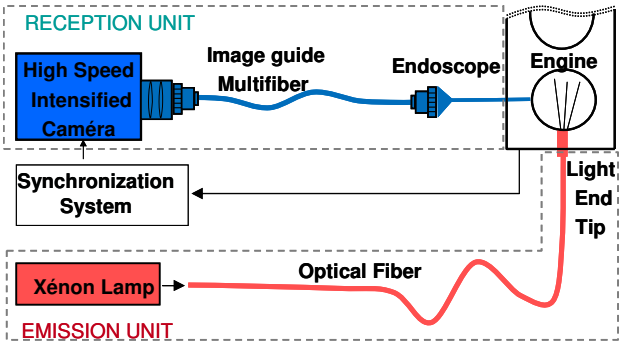


Figure 3: Optical configuration system

The "reception" unit is dedicated to the collection of images during the cold start and beginning of idle. The main device is an intensified high speed camera (USS La Vision). This camera can take a sequence of 16 images for each cycle (maximum speed is 1000000 pictures/s) at a 640x511 frame resolution. Due to the backup procedure between each sequence, the maximum rate is 4 Hz and that does not allow to take an image sequence from consecutive cycles but only from one out of two cycles in the best case. To collect the images from the combustion chamber, a 4 mm diameter endoscope is fixed on the engine cylinder head.

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Preliminary tests have shown the need of a specific reception configuration: due to the high engine vibrations level during cold start, an intensified camera can not be directly linked to the endoscope. So, a flexible optical multifiber has been installed between the endoscope and the camera to guide the images. It generates a considerable signal attenuation (about 60% losses). However, it is compensated by the high sensitivity of the intensified camera. Two optical lenses relay the images between the endoscope, the multifiber and the camera lens.

ENGINE OPTICAL PATHS AND CONFIGURATION

The engine is equipped with a modified cylinder head and combustion chamber to allow optical paths on cylinder 4 (see **Figure 4**).

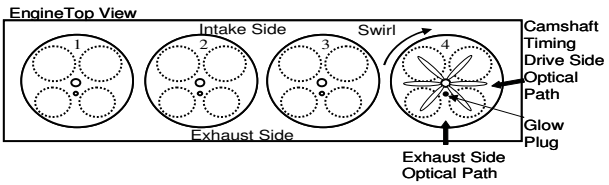


Figure 4: DW10 engine with optical paths on cylinder 4

Two boreholes are drilled in the cylinder head to insert at once the endoscope and the optical fiber to light up the chamber. As the most interesting phenomena occurs when the piston is close to TDC and the endoscope is flush mounted, the piston is machined on to create specific visualization paths to the combustion chamber even at TDC, as shown in **Figure 5**.

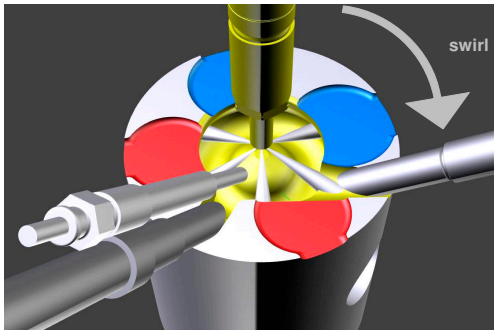


Figure 5: Optical paths on cylinder 4

Moreover, a 30° visualization axis endoscope is used to allow the observation of the injector and the glow plug area as well as the bowl dome (see **Figure 6**).

As said before, there are two optical accesses in the chamber: one on the engine exhaust side and the other on the camshaft timing belt drive side. It is possible to use them either to light up the chamber with the optical fiber or to collect the images with the endoscope.

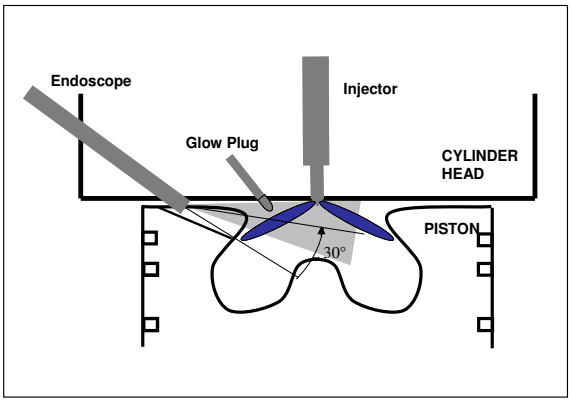


Figure 6: Visualization axis with 30° endoscope

Two configurations are possible:

- Exhaust side visualization (**Figure 7**). In this case, the injector is just behind the glow plug and three sprays are visible, one is very close to the glow plug and is coming to the visualization axis: "spray 1", one is on the right of spray 1: "spray 2" and one is on the left of spray 1: "spray 3". The bowl dome area is visible too, but the entire piston bowl bottom zone is hidden. In this configuration, the light comes into the chamber by the camshaft timing belt drive side access from the right of the image and can generate an illuminated point on the upper right side of the image.

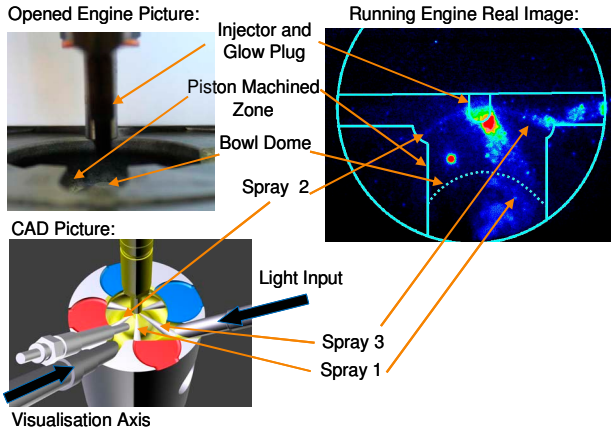


Figure 7: Exhaust side visualization configuration

- Camshaft timing belt drive side visualization (**Figure 8**). In this case, the injector and the glow plug are in the picture plane perpendicular to the visualization axis. Spray 1 is quite so in this plane, depending on the injector spray / glow plug angle. The light comes into the chamber by the exhaust side access, from the left of the image. This configuration is adapted to observe interactions between spray and glow plug.

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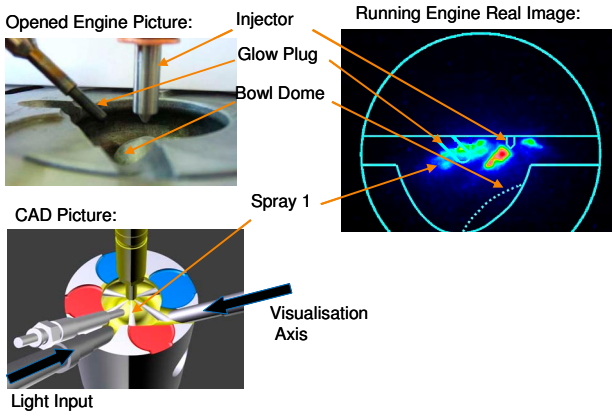


Figure 8: Camshaft timing belt drive side visualization configuration

IMAGE ACQUISITION PROCEDURE AND PROCESSING

As said before, the high speed camera can take several sequences of 16 images. An electronic device synchronizes image sequences acquisition with the engine cycles during cold operation. With this device, the operator can set up the images acquisition timing before the test.

Figure 9 shows a cold start test with optical measurements. Engine speed, cylinder pressures and camera signals are presented. The black marks "image cycles" indicate engine cycles when image sequences are acquired. For this test, they have been acquired on first and second cycles of cylinder 4 and then on every three cycles during the idle phase.

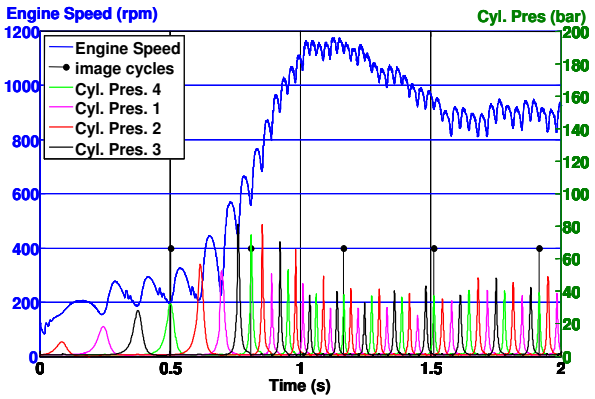


Figure 9: Engine speed, cylinder pressures and cycles with image sequences recorded during a cold start test

During a cold operation test, a high rate acquisition system (1/10°CA) records data from the engine. For each cycle, the cylinder pressure, injection command pulses and camera trigs are stored. Moreover, the apparent "net heat-release" rate [8] $dQ_n/d\theta$ is calculated using the following formula:

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta}$$

where:

γ : ratio of gas specific heats Cp/Cv
θ : crank angle degree
V : cylinder volume
P : cylinder pressure

The heat transfer losses are not considered in the case of the "net heat-release" rate. This parameter is preferred, compared to the "gross heat release" rate, due to the difficulty to evaluate heat transfer losses during transient cold start (high variations).

Figure 10 shows the first firing cycle on cylinder 4, during a cold start test. The injection pulses, cylinder pressure and calculated heat release rate of cylinder 4 are presented. Event like the fall of heat release rate during the Main injection phase can be noted. As said before, the images timing is set up by the operator and then **Figure 10** presents also the "image trig" corresponding to the crank angle of image acquisition during the cycle.

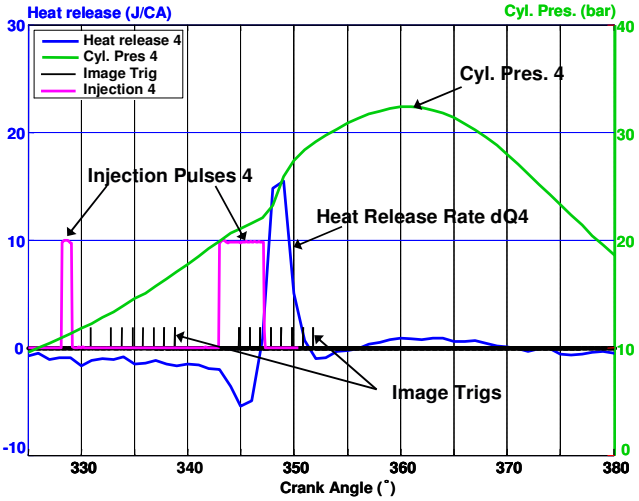


Figure 10: First firing cycle (Cyl. 4) during a cold start test - injection pulses, cylinder pressure, heat release rate and images trigger signal

Figure 11 presents images and signals of the first firing cycle (cyl. 4) of the test.

This images sequence permits to observe phenomena like the combustion of Pilot injection at 331 - 334°CA and the combustion of Main injection at 348 - 352°CA linked to the heat release signal. In this way, in cylinder visualization allows to affirm that Pilot injection is partially but really burning, what does not appear clearly on cylinder pressure evolution neither on heat release. Taking into account that Pilot injection combustion has a

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beneficial effect on Main 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.

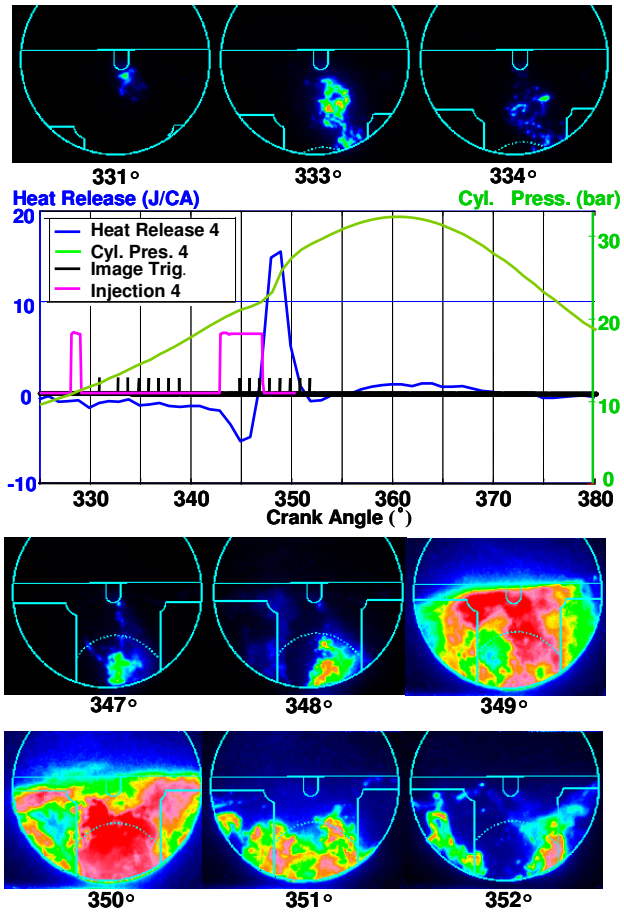


Figure 11: First firing cycle (Cyl. 4) during a cold start test – images relative to Pilot and Main Combustion start

For each test, similar acquisition and post processing procedures are adopted.

NUMERICAL SET UP

INTRODUCTION

The aim of the numerical part of the study is to bring information on the physical mechanisms occurring during the start of a Diesel engine with low CR in low temperature conditions. Accurate prediction of auto ignition in the engine cycle or prediction of the engine start ability is not expected. The aim of the present numerical study is to understand the mechanisms inducing the first combustion

DESCRIPTION OF THE 3D CFD CODE

The three-dimensional simulations were performed using IFP-C3D code [9]. This one 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) code solves the Navier-Stokes equations using an ALE-extended (Arbitrary Lagrangian Eulerian, see [10], [11] and [12] for more details concerning this model and its validation) finite volume method on unstructured and conformal hexahedral meshes. The code uses the well known time splitting decomposition. The temporal integration scheme is largely implicit.

For turbulent combustion, the 3-Zone Extended Coherent Flame Model (ECFM3Z) is used [13]. The auto-ignition prediction and the influence of chemistry on reaction rates are provided by the TKI (**T**abulated **K**inetics of **I**gnition) auto-ignition model [14]. To obtain a realistic spray modeling during the injector needle motion, the Transient Injection Conditions (TIC) model [15] is used.

Spray Modeling

The spray of the injector is discretized in parcels (set of droplets with same characteristics). The radius of the injected droplets is equal to the effective radius of injector hole. Turbulence model is k-ε and the Wave/FIPA model [16] is used to model the evaporation and the break-up. It may be specified that all the parameters of the injection model were fixed in order to get a good agreement with experimental measurements and visualizations performed in "normal" running conditions. For the present study (cold start, low temperature) the parameters of this model were not modified due to a lack of experimental visualization for the present running conditions. Evolutions of these spray parameters for such conditions may increase the accuracy of the model for cold start representation.

Liquid Fuel Film Model

Taking into account the wetting of walls by the injected fuel is necessary in such conditions ([17] and [18]). The liquid fuel film on walls is modeled using an in-house Lagrangian model based on the O'Rourke and Amsden [19], [20] model for the formation, the evaporation and the splashing. This model was improved using the work of Xu and Han [21], [22]. 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.

The interaction with the spray induces, of course, mass evolution but changes in terms of energy and tangential momentum too. Moreover, sub models were introduced in order to take into account droplet rebound and splashing. The interaction between the liquid film and the walls depends on heat fluxes and adherence conditions.

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