Studies of DI Diesel Engine Cold Start Combustion in an Optical Engine

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A study on ignition and early combustion development has been performed in an optical engine at in-cylinder thermodynamic conditions representative of those occurring during the cold start of a modern DI Diesel engine for passenger cars at an ambient temperature of -20ºC. A general description of the process has been derived from in-cylinder pressure analysis and high speed imaging, and the effect of most relevant engine parameters has been analysed providing guidelines for cold start optimisation.

Introduction

Cold start at low temperatures in current D.I. direct engines is a problem which has not been properly solved yet and becomes particularly critical with current trend to reduce engine compression ratio [1]. To promote fuel ignition a heating plug is usually installed in the cylinder head of passenger car DI diesel engines.

Although it is clear that there are some key factors whose control lead to a proper cold start process, their individual relevance and relationships are not clearly understood [2-6]. Thus, efforts on optimisation of the cold start process are mainly based on a trial-and-error procedure in climatic chambers at low ambient temperature, with serious limitations in terms of measurement reliability during such a transient process, low repeatability and experimental cost [7-9].

This paper presents a novel approach for the study of the first injection cycle of a light duty engine at -20ºC during the starting process, combining visualization tests in an optical engine and heat release analysis for individual cycles. Systematic studies, in the borderline between ignition success and misfiring are performed so that the relevance of engine parameters on ignition success can be assessed. On the basis of these studies, a description of the combustion process under cold start conditions has been derived.

Experimental facility and methodology

Target in-cylinder conditions to be reproduced in the optical engine around top dead center have been estimated from experiments in climatic chamber similar to those made by Payri et al [7]. Peak in-cylinder pressure is between 25 and 30 bar, and peak in-cylinder temperature is between 335 – 350ºC.

A conventional single-cylinder research engine with optical access through the piston bowl, in a fully equipped test cell has been modified for the study of cold start in the following aspects [10]:

- Reduction of compression ratio and control of intake air temperature to achieve in-cylinder peak temperature under motored, but respecting distance between piston and cylinder head at TDC so that most flow patterns are not severely modified.
- Reduction of engine speed to the lowest controllable value (250 rpm) so that engine dynamics is reproduced as closely as possible.
- External supercharging to achieve peak pressure values of the real engine during cold start.
- Control of temperature of all engine fluids (water, oil and fuel) to the minimum value achievable to avoid moisture condensation problems on engine surfaces which allows long-duration systematic experiments to be performed.
- External operation of the injection system to allow skip-fire mode to avoid temperature transients, to reduce instability problems near the operation limits of the injection system itself, to avoid any engine ECU corrections, to provide full flexibility to change any injection parameter, and to suppress the influence of residuals upon ignition.
- Measurement of instantaneous intake and exhaust mass flow rate, so that blow-by can be measured indirectly. Such a parameter, which is not usually controlled in optical engines but can be severely influenced by piston-rings wear, is crucial for the proper estimation of mass trapped in the cylinder and, consequently, the real bulk gas temperature.
- External control of glow plug power to control heat transfer.
- Flexibility for orientation between sprays and glow plug.

Preliminary tests showed that the ignition process under cold-start conditions can be extremely variable. Thus, the analysis of consecutive combustion cycles (with 20 motored cycles between them) have shown different combustion patterns appearing randomly, as shown in figure 1: in some cycles fuel does not ignite, in some others ignition takes place properly and in some others ignition occurs too late to be considered as successful ignition for cold start.

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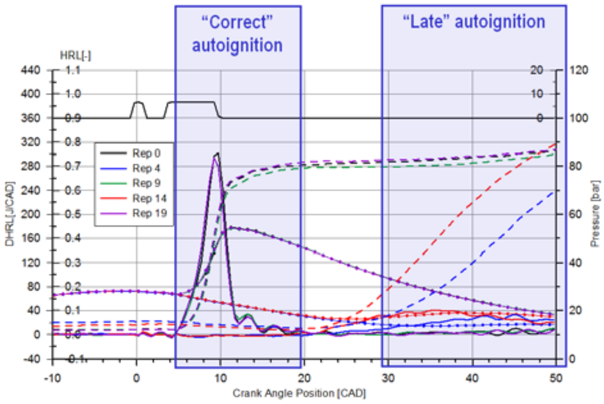

Fig.1. Combustion patterns for individual cycles for a single test.

Thus, an analysis methodology was defined for this particular kind of studies combining different sources of information:

- Conventional heat release analysis derived from in cylinder pressure traces, but applied to individual cycles and adapted in some few aspects,
- Light radiation registered with photodiodes and photomultipliers using or not interference filters to track different radicals,
- High speed imaging with a CMOS camera at 6000 frames per second under different optical configurations and
- Other complementary sources of information such as injection rate and spray momentum flux measurements or outputs from modeling.

Results

In order to improve knowledge about the process, only pilot injection test cases (figure 2) have been considered in addition to single+main injection cases (figure 3). A general description of the combustion process has been derived, for conditions in which combustion succeeds:

The injected fuel mixes with air, but due to the low air and engine temperatures evaporation before the start of combustion is really poor. According to calculations, only around 10-20% of the injected mass is evaporated, and most of the evaporation proceeds during the injection event. The rest of the injected mass is deposited on the piston surface in liquid state. If heat release starts, some additional evaporation occurs due to combustion-induced heating. Limitations in evaporation are one of the main hurdles for obtaining an acceptable combustion process.

After pilot mass is evaporated, most of it undergoes a long autoignition process. Fuel injected close to the glow plug starts burning around 3 ms after the start of injection. However, due to the low amount of fuel vapour, reaction does not propagate to the rest of the chamber, and heat release is too low to be detected.

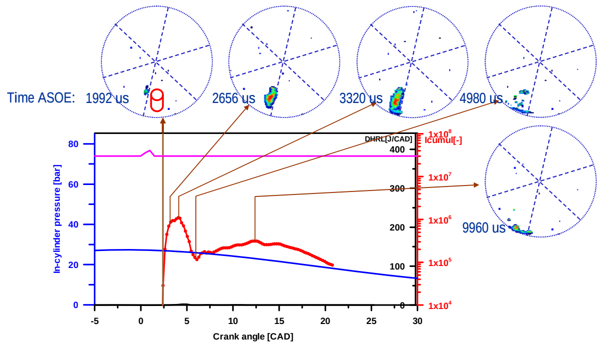

Fig. 2. Image sequence of the pilot flame combustion with cycle-resolved evolution of pressure and luminosity.

Since energy required for fuel evaporation stems not exclusively from the heating plug but also from the surrounding air, this provokes a decrease of local gas temperature which could cause flame quenching and slow down or prevent proper flame propagation.

So, the rest of the fuel of this and the other sprays further away from the glow plug will be burnt later, only if a second injection (main) is performed.

If main injection is introduced into the chamber in the period where pilot mass autoignition occurs, ignition delay for main injection is within the injection event duration. A very steep heat release is obtained, usually with a single peak. Images have shown that the intense heat release period corresponds to the time interval where a reaction front is travelling throughout the combustion chamber (see OH images of fig. 4). This front burns the prepared mixture. After the peak, injection is usually over. Due to the higher temperature, liquid fuel from the piston wall can evaporate and burn and a residual combustion process can be observed during the rest of the combustion process. In spite of the low intensity of this late combustion period, the amount of energy may reach around 20-30% of the total energy release. However, this phase is really difficult to control.

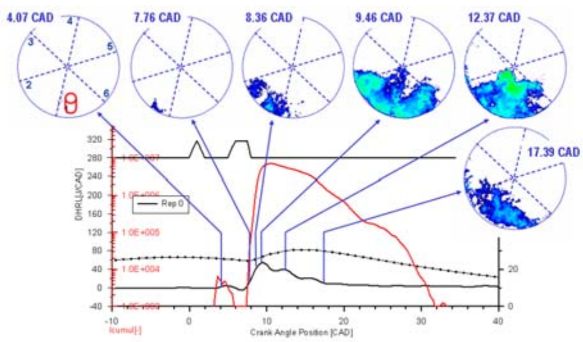

Fig. 3. - Image sequence of the pilot+main flame combustion with cycle-resolved evolution of pressure, luminosity and rate of heat release.

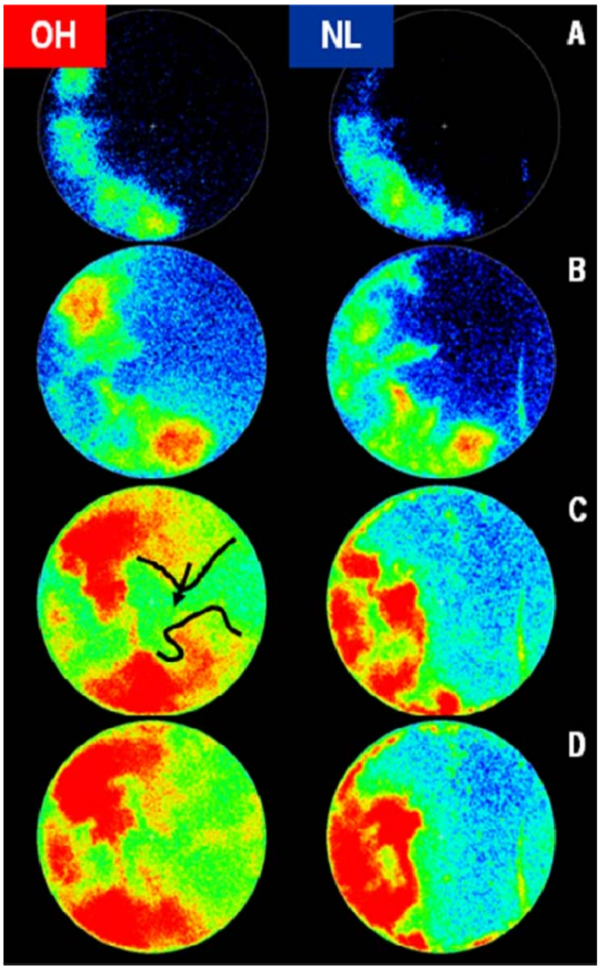

Figure 4. Simultaneous OH (left) & natural luminosity images (right) in a single cycle.

A wide range of geometrical and operating parameters have been considered to identify and analyse the factors with influence upon cold start success in the case of using a conventional plug.

The election of an adequate injection strategy (together with a proper selection of the angle between the spray and the plug) appears as a critical factor for proper cold start: pilot injection timing and quantity must be such that ignition occurs in the vicinity of the heating plug. Then, if the delay between the pilot and main injection pulses and the amount of fuel in the main injection are not chosen conveniently, flame quenching can occur and combustion will not progress.

Pilot injection mass seems to be influential in the amount of heat release generated by the pilot combustion. However, heat required to vaporize pilot fuel may also have a large influence on this combustion process.

Main injection fuel quantities also play a role. Due to the low evaporation rate, larger main injection masses mean a larger amount of vapour fuel, and thus a higher heat release, once the ignition phase has been overcome.

Injection pressure plays a major role on the ignition success and combustion stability. Results show that low injection pressures improve largely ignition probability, since flow velocities are low and consequently, energy dissipation rates. However, if combustion progresses, higher injection pressures lead to better mixing and higher imep is obtained.

Other factors analyzed (e.g. injector-glow plug orientation and distance, glow plug temperature, in-cylinder pressure and temperature, or swirl intensity) can modify or modulate the picture described above on the combustion process. However, further research is necessary to clarify their influences

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