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Ignition and combustion development for high speed direct injection diesel engines under low temperature cold start conditions

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ABSTRACT

Diesel engine cold start is an important issue for current technology at low (below 0 °C) temperatures and for future applications. The aim of this work is to develop a description of how, when and where does fuel spray ignition occur in a glow-plug assisted engine under simulated low temperature cold start conditions. In-cylinder pressure analysis is combined with high speed visualization in an optical engine. A pilot plus main injection strategy is used. Visualization results show that pilot ignition occurs in the vicinity of the glow plug, and strongly influences main combustion initiation. Main combustion starts from the pilot flame, and propagates to the rest of the combustion chamber showing a strong visible reaction zone. After end of main injection, the rapid leaning of the mixture suppresses the strong radiation, and OH radiation is observed to progress to the rest of the combustion chamber. The combustion process shows a strong scattering, which has been quantified by combustion parameters. At higher rail pressures scattering increases, which eventually inhibits combustion initiation. However, if ignition occurs at higher rail pressures, cycle performance is better.

1. Introduction

In spite of all the improvements made in diesel technology to the date, starting at low (below 0 °C) ambient temperatures is still a problem which has not been properly solved. Low ambient temperatures result in low peak compression temperature, which causes poor vaporization. Low peak pressures are also achieved due to the high blow-by level as a result of engine block temperature, low engine speed and low intake pressure. Such conditions lead to a very poor fuel air mixing process which, in addition to the poor vaporization, can inhibit fuel ignition under this particular and strongly transient engine situation provoking unburnt hydrocarbon emissions [1]. In order to promote ignition, air temperature within the combustion chamber is increased by means of ignition aids, as intake heaters or glow plugs [2,3]. For current automobile diesel engines these aids become necessary for temperatures below −11 °C [4] and for future applications with reduced compression ratio [4–7] these aids are necessary below 10 °C [4].

Most of the studies on low temperature cold start are focused on trial-and-error procedures and carried out in climatic chambers, but recently they have become more systematic aiming at engine cold start optimization. Studies performed on climatic chambers [3,8–10] have certainly delivered valuable information but several measurement uncertainties and the incapability of using extra diagnostic tools have prevented from making a detailed explanation of this combustion process. Laget et al. [6] show a more systematic approach to the problem in which in-cylinder analysis, endoscopic visualization and CFD modeling are coupled in order to identify the pre-glowing glow plug duration, nozzle tip protrusion, injector spray angle and cranking speed as key parameters with influence on startability. Later, a more detailed analysis of the combustion sequence have been presented by Perrin et al. [11], in which the location of the first ignition spots are shown to appear in the vicinity of the glow plug, together with the influence of some other parameters like swirl motion and injection pressure. Similar work has been presented by Chartier et al. [12], who show how combustion starts close to the glow plug and does not spread to the whole chamber.

All previous papers evidence the current interest of engine community to understand and optimize engine performance under cold start conditions. Most of these works address the optimization of a particular engine or vehicle, studying the effect of specific engine parameters on cold start ease. But only few of them try to go deeper into an explanation on the sequence of events leading to successful combustion initiation. The main objective of this paper is to give a detailed description of the combustion process within the combustion chamber and the phenomena that lead to combustion initiation. The study will be performed in a single-cylinder optical engine that has been adapted to simulate in-cylinder conditions similar to those of a real engine operating at low temperature cold start [13]. After this introduction, the experimental and

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Nomenclature

I	light intensity, dimensionless
m	mass, kg

Subscripts

cumul	accumulated
f	fuel
main	main injection
pilot	pilot injection

Abbreviations

ASoI	after start of injection
CAD	crank angle degree
CE	combustion efficiency
CFD	computational fluid dynamics
CR	compression ratio
ECU	engine control unit
EoI	end of injection
EVO	exhaust valve opening
FWHM	full width half maximum
HRL	heat release law
IL	integrated luminosity
IMEP	indicated mean effective pressure
IVC	intake valve closing
LD	luminosity delay
LHV	lower heating value
NL	natural luminosity
ROHR	rate of heat release
SOC	start of combustion
SoI	start of injection
TDC	top dead centre
UV	ultraviolet

calculation tools and methodology used for the study are presented. Then, an evaluation of combustion scattering is made, followed by a general description of the combustion event. Later on, the effect of rail pressure on combustion is evaluated, and finally a discussion on the controlling parameters for low temperature cold start combustion is made. Finally, the main outcomes of this work are presented.

2. Tools and methodology

This section presents a description of the experimental and theoretical tools employed for this study. Experimental information has been obtained in a specially adapted facility in which in-cylinder cold start conditions can be reproduced in an optical single cylinder engine at room temperature. Theoretical tools consist on chemical kinetics and CFD simulations that have been carried out in order to help understand the experimental results in terms of physical variables.

2.1. Experimental facility

This sub-section is a brief summary of the engine description, the solution adopted in order to reach cold start conditions and a description of the fuel injection system. A more detailed explanation about the facility adaptation and its capabilities has already been presented in [13].

2.1.1. Engine description

The optical engine used in the present study, sketched in Fig. 1, is a 4-valve and 0.55 l displacement single cylinder engine. The engine is equipped with an elongated piston with a cylindrical bowl, with dimensions of 45 × 16 mm (*diameter* × *depth*), which allows optical access to the combustion chamber through a sapphire window placed in its bottom. Below the piston bowl, an elliptical UV mirror is placed on the cylinder axis. And, in front of the mirror, the high speed camera is positioned to record radiation that comes from the combustion chamber.

The facility has been modified to reproduce the first injection cycle of the starting sequence of a passenger car engine at −20 °C. Specifically, thermodynamic conditions within the combustion chamber and low engine speed can be reproduced systematically. In order to reach the same peak in-cylinder temperature, the compression ratio has been reduced (16:1–8:1) and intake temperature has been controlled at 30 °C. Compression ratio has been reduced by placing an aluminum piece (shown in Fig. 1), with 42 mm height and internal diameter slightly larger than the engine bore, between the cylinder head and the engine block. Peak in-cylinder pressure has been set controlling the intake pressure. Finally, the electronics of the electrical motor have been modified so that stable operation at 250 rpm is ensured.

A standard glow plug [2] (Fig. 1) is used for the study. At the standard configuration, the tip protrudes 3 mm into the combustion chamber from the cylinder head plane, it is located at 11.5 mm from the cylinder axis and it is operated at a constant nominal tension of 11 V.

2.1.2. Fuel injection system

A common rail injection system with piezo injectors is operated externally to ensure stable behavior, avoiding uncertainties associated to corrections made by the ECU. The injector used is equipped with a microsac nozzle with seven holes (with a nominal diameter of 0.142 mm). It is centered in the cylinder and vertically mounted as shown in Fig. 1. In that way, spray orientation with respect to the glow plug can be modified by rotating the injector around its axis. For this study, one of the sprays has been oriented at 12° from the glow plug in clockwise direction. Under this configuration, the minimum distance between the glow plug surface and the spray has been estimated to be 2.3 mm.

Injection is performed at a reduced frequency (one injection every 40 cycles) to avoid engine temperature increase, speed instability in case of ignition and to reduce window fouling. Each test consists of 20–30 injection cycles recorded under the same engine conditions.

2.1.3. Conditions of the study

For the tests presented in the following sections basic engine conditions will remain unchanged: engine speed 250 rpm; intake air temperature 30 °C, with which 345 °C are obtained as peak in-cylinder temperature; oil, fuel and water temperatures are fixed at 30 °C and intake pressure is set to reach target peak compression pressure (27 bar). Two levels of rail pressure, similar to those reached during the starting sequence in a real engine at low temperature, have been tested, namely 250 and 370 bar. The former is the lowest possible value for stable behavior at short injection pulses. And the latter is a value close to the limit above which ignition can not been achieved. The injection strategy consists of two separated pulses. In the first one, a small amount of fuel is