

An Investigation on Mixing and Auto-ignition using Diesel and Gasoline in a Direct-Injection Compression-Ignition Engine Operating in PCCI Combustion Conditions

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Jesus Benajes, Ricardo Novella, Antonio Garcia and Vicent Domenech
Universitat Politècnica de Valencia

Russ Durrett
GM R&D Center

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ABSTRACT

Most of the new Diesel combustion concepts are mainly based on reducing local combustion temperatures and enhancing the fuel/air mixing with the aim of simultaneously reducing soot and NO_x emissions. In this framework, Premixed Charge Compression Ignition (PCCI) has revealed as one of the best options to combine both low emissions and good combustion controllability.

During last years, PCCI strategy has been widely explored using high EGR levels and different early or late injection timings to extend the ignition delay. Recently, the use of lower cetane fuels is under investigation. Despite the great quantity of research work performed, there are still some aspects related to PCCI combustion that are not completely well known.

In this paper an experimental and numerical study is carried out focused on understanding the mixing and auto-ignition processes in PCCI combustion conditions using Diesel and Gasoline fuels.

For this purpose, a parametrical study has been performed varying EGR, injection timing, and fuel type in a High Speed Direct Injection (HSDI) Diesel engine. A detailed analysis in terms of air/fuel mixing process has been also developed by means of a 1-D in-house spray model.

Results using Diesel fuel show how increasing the ignition delay by advancing the injection timing together with high EGR levels extends the mixing time between the End of Injection (EoI) and the Start of Combustion (SoC). As a consequence, lower local equivalence ratios are achieved. However, it has been confirmed how the use of gasoline has more impact on air/fuel mixing process and auto-ignition delay than any other engine setting investigated with the diesel fuel.

INTRODUCTION

In the last decades, the entire world is facing two of the most important threats in its recent history. On the one hand, the global warming caused by the accumulation of particular gases, known as “greenhouse gases” and, on the other hand, the foreseen shortage of fossil fuels, which are right now the world's primary energy resource, is expected to force the society to accept important challenges related to energy availability. Undoubtedly, future internal combustion engines (ICE) in general, and those applied in transport applications in particular, will play a major role in the short and long term management of these two environmental risks. The relevance of ICE can be easily understood considering that oil-based fossil fuels are nowadays the main input; whereas CO₂, which is one of the more aggressive “greenhouse gases”, is the main output of these thermal engines.

Continuing with the evaluation of the context and focusing on transport applications, the most widespread powerplants

equipping road vehicles are the gasoline (or spark-ignition, SI) and the diesel (or compression ignition, CI) internal combustion engines. Diesel engines use oil-based fuel 25-40% more efficiently than gasoline engines. Therefore, they provide a promising means of lowering fuel consumption (and CO₂ emissions) until a more sustainable solution is found [1].

On the other hand and as a main drawback, the diesel engine is also well known as a significant source of pollutant emissions, including nitrogen oxides, unburned hydrocarbons, carbon monoxide and particulate matter (mainly soot), and stringent regulations are being introduced around the world to limit its environmental impact. More specifically, conventional diesel fuels used in current diesel engines have cetane numbers (CN) greater than 40 and will auto-ignite very quickly after the start of injection into the cylinder. Particularly at high loads, fuel continues to be injected after the combustion has started and this leads to high NO_x and soot. If the mixing is accelerated or if the chemical reaction is slowed down, autoignition can be made to occur after the fuel and air are better mixed, and soot levels can be reduced. Consequently, on this concern, it would be desirable to have a fully premixed combustion. NO_x levels can be reduced by reducing combustion temperature by either running lean, pre-mixed or using EGR [2] (Exhaust Gas Recirculation). In fact, outstanding technology is currently used in advanced diesel engines, making them expensive and complicated, to counteract the high ignitability of the diesel fuel in order to promote premixed combustion. Thus high injection pressures and high swirl are used to increase mixing rates while high levels of cooled EGR are used to delay autoignition; this in turn requires higher boost pressures to achieve the required loads. Even then, with conventional diesel fuels, low NO_x and low smoke with partially premixed CI combustion is possible only at low loads. Modern engines still require heavy after-treatment systems to further reduce NO_x and particulates, making the powertrain even more complicated and expensive. Moreover, regulations on emissions from diesel engines are becoming more stringent worldwide. Hence there is a great deal of interest in developing engine combustion systems that offer the efficiency of a diesel engine, but with low smoke and low NO_x, trying to overcome complex (and expensive) after-treatment systems.

Several operating strategies have been employed to promote premixed and low-temperature combustion in CI engines. In the Toyota UNIBUS (Uniform Bulky Combustion System) a double-injection strategy is used [3] with some fuel injected very early in the cycle to get better mixing with air. Nissan's MK (Modulated Kinetics) design utilizes high levels of EGR in conjunction with high swirl [4] and late injection to promote fuel/air mixing by increasing the ignition delay. Reduction of NO_x could also be achieved by PREDIC (Premixed Lean Diesel Combustion) at low to part loads and

its evolution MULDIC (Multiple Stage Diesel Combustion), with multiple fuel injectors and injections, at higher loads [5]. In homogeneous-charge compression-ignition (HCCI) fuel and air are fully premixed, as in a spark ignition engine, and compressed till the charge auto-ignites. In modern direct-injection (DI) diesel engines with common rail injection systems, HCCI combustion can be obtained by injecting the diesel fuel very early in the cycle, giving it enough time to mix completely with air. However, with HCCI, the phasing of the heat release will be determined by the initial conditions of the mixture at the start of the compression stroke and the auto-ignition characteristics of the fuel. There is no in-cycle control of combustion phasing with HCCI unlike with the spark timing in SI engines or the injection timing in diesel engines. Hence HCCI combustion is very difficult to control and is also limited to low loads. Practical CI engines at medium-to-high load always operate in a fuel injection timing range - injection near TDC (Top Dead Centre) - where combustion phasing can be varied by varying injection timing.

According to this, it becomes clear that a premixed (to avoid soot), low-temperature (to avoid NO_x) compression ignition combustion can be an interesting way to achieve a clean and efficient engine. However, using a high reactivity fuel as the diesel fuel for this purpose leads to a complex and expensive engine design. A way to overcome this shortcoming is to change and control the reactivity of the fuel. Kalghatgi and co-workers have demonstrated both in large [6,7] and small [8,9] single-cylinder research engines that if a gasoline-like fuel is injected near, but before, TDC, it ignites much later than diesel fuel and combustion occurs when fuel and air have had more chance to mix. If the same amount of gasoline is injected early (e.g. before 50 CAD BTDC) at the same conditions i.e. with fully premixed, HCCI conditions, ignition might not occur at all. Thus the heterogeneity is essential for combustion to occur but the long ignition delay makes combustion happen when fuel and air are better mixed: fuel and air are "premixed enough" but must not be fully premixed.

From the previous discussion it can be deduced that, on the one hand, partially premixed charge is a promising combustion concept to attain low emissions in Compression Ignition engines. On the other hand, the use of low cetane fuels as gasoline can solve a great part of shortcomings derived of the use of diesel fuel in PCCI combustion. Nevertheless, more research is needed in order to better understand how affects mixing and autoignition processes the use of gasoline fuel in CI engines.

2. OBJECTIVES AND METHODOLOGY

The main objective of this paper is to investigate the mixing and autoignition processes in an engine operating under PCCI combustion conditions.

For this purpose, the three following parameters are aired:

- The mixture reactivity by means of different oxygen concentrations in the intake.
- The thermodynamic gas conditions (pressure, temperature and density) during the injection process through variation of injection timings.
- The cetane number of the fuel. Commercially available diesel and gasoline from a petrol station are tested.

As a general methodology, a combined study is proposed combining both experimental results and 1-D model results in order to better understand the behavior of this combustion mode.

The experimental study is performed at a low-load (25%) engine operation mode. The injection pressure remains constant during this study at 1200 bar. This is a pressure high enough to provide short injection duration with sufficient fuel mass for this low load and to achieve a PCCI combustion mode. The start of combustion always must occur after the end of injection. The fuel mass injected is maintained constant 15.4 mg/str for all cases.

The injector used is a Bosch piezoelectric CRIP 3.3 containing 7 nozzle holes with a diameter of 97 microns. A small nozzle diameter allows better atomization of the liquid fuel and promotes the physical mixing process.

It is very important when studying the autoignition and mixing processes to control the conditions during the injection event. This allows a better understanding of the phenomena involved and helps ensure the repeatability. Thus, the tests are conducted in skip-fire mode; only one injection is performed every 30 cycles, in order to avoid temperature transients due to cycle to cycle combustion dispersion. For each operation point, ten cycles are recorded.

Since a skip fire mode is used to carry out the experimental test, the oxygen concentration variation is performed using a synthetic EGR system. Nitrogen is substituted for the EGR gas which greatly simplifies the system ensures a controllable gas composition without an excessive time to adjust the facility. The concept consists of decreasing the O₂ concentration at the inlet manifold by increasing the amount of N₂ (substitution EGR, the total mass is kept constant). The oxygen concentration variation is shown in [Table 1](#). An injection timing sweep is carried out to observe the effects of

density and temperature on the autoignition and mixing processes. The main test settings are presented in [Table 1](#).

Table 1. Tests settings

	Units	Value
T inlet	[K]	303
Pinlet	[bar]	2
Mass	[mg/st]	15.44
Pinj	[bar]	1200
Speed	[rpm]	750
XO2	[%]	[7 – 18]
SoI	[° b TDC]	[-24 – -14]

Table 2 contains the main properties of both the gasoline and diesel fuels. A critical evaluation of the effects of these differences in the fuel main properties on the autoignition and mixing processes is also included in the paper.

Table 2. Characteristics of fuels used in the study

Fuel	Diesel	Gasoline
Density [Kg/m ³]	882	765
Viscosity [Centipoise]	2.8	0.37
Octane Number [-]	15-25	98
Cetane Number [-]	52	5-12
Reid Vapour Pressure, [psi]	0.2	10
Lower heating value [Kj/Kg]	42651	44542

3. EXPERIMENTAL SETUP AND TOOLS

Experimental tests are carried out on a single cylinder DI Diesel engine for better control of the operating conditions [10]. The Engine specifications are presented in [Table 3](#).

Table 3. Main research engine characteristics

Engine Type	DI Diesel Single Cylinder
Bore x Stroke	85x 96 mm
Displacement	0.5447 l
Compression Ratio	14.5
Fuel Injection System	Common-rail. Piezoelectric system

The engine is installed in a fully instrumented test cell, with all the auxiliary facilities required for the operation and control. [Figure 1](#) shows a schematic diagram of the installation.

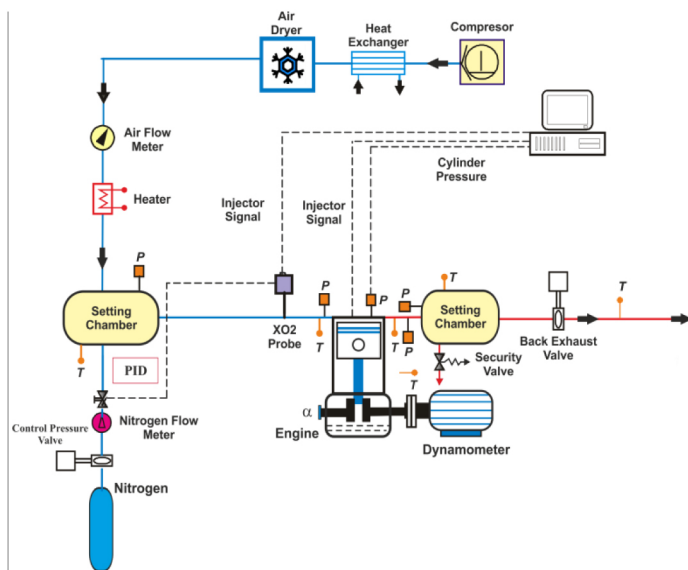


Figure 1. Schematic diagram of the Complete test cell

A screw type compressor supplies the air which passes through an air dryer. The thermodynamic gas conditions were measured in the volumetric air flow meter to calculate the air density and provide the intake air flow rate measure. The gas pressure is measured in the intake settling chamber while the intake temperature measured in the intake manifold after mixing with N_2 . The intake pressure and temperature are precisely controlled using the screw compressor and electric heater. The exhaust backpressure produced by the turbine in the real engine was replicated by means of a backpressure valve placed in the exhaust system, controlling the pressure in the exhaust settling chamber.

The decrease in oxygen concentration is carried out with the increase of nitrogen into the mixture with fresh air. A system for measuring the mass flow rate of nitrogen [g/s] is installed in this facility. This nitrogen reaches the setting chamber where it mixes with the fresh air. After mixing in this large volume, the intake manifold has a lambda sensor for monitoring the oxygen concentration XO_2 is controlled by increasing or decreasing the mass flow rate of nitrogen. With this system, XO_2 can be reduced to as low as 6.5% with 3.2 bar of nitrogen inlet pressure. The system operates without recirculation, where the nitrogen is not re-introduced into the combustion chamber in contrast with the normal exhaust gas recirculation systems (EGR).

The temperature is measured with a sensor in the intake manifold and is regulated with a heat exchanger which keeps it at constant value. In order to ensure the required XO_2 mass flow rate, the exhaust pressure was maintained at 0.2 bars above the intake pressure. The specific XO_2 rate is controlled by means of a lambda probe calibrated to work in these conditions.

At each engine operation point, the in-cylinder pressure traces from a piezoelectric transducer were recorded during 10 consecutive skip firing engine cycles in order to study the cycle to cycle dispersion in engine operation.

The recorded values of in-cylinder pressure were processed by means of a combustion diagnosis code CALMEC [11,12]. Valuable information can be extracted, especially the rate of heat released (RoHR).

The injection rate and spray momentum are measured experimentally on a test rig for the nozzle used. Those parameters are important for an adequate definition of the fuel injection velocity [13] which will influence the mixing process during and after the injection event [14].

The data collected on the test rig are used as input for an in-house 1-D spray model [15,16] for the calculation of the evolution of the local equivalence ratio after the EOI and before the SOC. This 1-D model is used in order to clarify the mixing process in response to variations of the injection timings, oxygen concentrations and fuel types.

4. RESULTS AND DISCUSSION

4.1. EXPERIMENTAL WORK

Regarding the literature, it seems important to evaluate thermodynamic conditions during the injection process due to their importance in autoignition phenomena after the EoI. Thus, with the aim of obtaining information during the injection period, an initial analysis is performed.

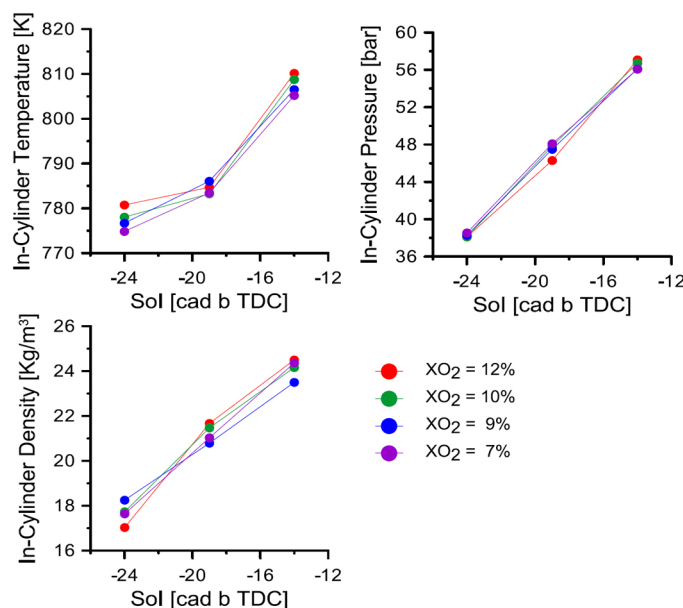


Figure 2. In-cylinder conditions for diesel and gasoline experiments