

UV-Visible Spectroscopic Measurements of Dual-Fuel PCCI Engine

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ABSTRACT

In this work, optical diagnostics were applied in a transparent DI diesel engine equipped with the head of Euro5 commercial engine and the last generation CR injection system. In order to realize the PCCI combustion the injection of neat bio-ethanol was performed in the intake manifold and European commercial diesel fuel was injected into the cylinder. Different amounts of bio-ethanol were injected in order to create PCCI combustion with high levels of pre-combustion mixing, and to ensure low equivalence ratio and low flame temperatures too. UV-Visible imaging and spectroscopic measurements were performed in the engine in order to investigate the autoignition of the charge and the combustion process, respectively. In particular, the detection of the species involved in the combustion, like OH, HCO, and CH, was performed. The relevance of the radicals and species on PCCI were evaluated and compared with the data from thermodynamic analysis.

INTRODUCTION

One of the major contributors to the greenhouse effect is the transport sector due to the heavy increasing of the traffic level. Moreover, since the transport level is substantially rising, especially in developing countries, reasonably political decisions must be taken to address this problem now and in the future. In addition, the dwindling supply of mineral fuels is becoming a limiting factor for the developing countries. Important efforts to solve this problem are to replace fossil source energy with bio-energy. In the transport sector this means either introducing bio fuels or blending bio fuels with petroleum-based ones for use with present vehicle fleets. The two alternatives are not mutually exclusive. However, blending bio fuels has two advantages: 1) even if quite low blending concentrations will be used the total petroleum-

based fuel volumes will be substituted by bio-fuels; 2) the present infrastructure for distributing the blending fuels can be used. Biofuels for diesel engine include vegetable oils and biodiesel, and could be also used as pure fuel [1, 2]. On the other hand, alcohols like bio-ethanol are generally blended with gasoline or used as neat fuel in optimized spark ignition engines; nevertheless their use in compression ignition engines must be considered too [1, 3]. As reported by many authors, bio-ethanol blended with diesel fuel, at different concentrations, is able to power compression ignition engine [3,4,5]. It was proven that, according to physical-chemical properties, bio-ethanol/biodiesel blends up to 15% ethanol can run a diesel engine only by improving the flash point [5].

On the other hand, advanced combustion strategies could also help to reduce pollutant emission keeping constant the performance. Premixed charge compression ignition (PCCI) has been shown to be a promising strategy to simultaneously reduce NO_x and soot emissions while realizing improved fuel economy. PCCI combustion uses high levels of pre-combustion mixing to lower both NO_x and soot emissions by ensuring low equivalence ratio and low flame temperatures [6]. The high level of pre-combustion mixing results in a primary kinetics controlled combustion process. In order to realize this circumstance, it is necessary to increase the ignition delay of the diesel fuel that is highly reactivity. In this work, bio-ethanol, that is a relatively un-reactive fuel, is added to the intake air and dual-fuel PCCI combustion is realized [7, 8]. European commercial diesel fuel and pure bio-ethanol were used. The first one was injected directly in-cylinder. On the other hand, bio-ethanol is not soluble or has very limited solubility in diesel fuel. The solubility of the bio-ethanol and diesel mixture is dependent on the hydrocarbon composition of the diesel fuel, water content of the blends, and ambient temperature [9]. In order to prevent this problem, the authors decided to do not blend the two fuels in

the tank but to mix it directly into the cylinder injecting the bio-ethanol in the intake manifold. In this way no additive was necessary to stabilize the blend and the desired amount of bio-ethanol to be injected can be chosen. Measurements were carried out in a single cylinder optical engine. Several injection strategies were tested varying the amount of bio-ethanol. Because this combustion is a chemical-reaction governed process, the knowledge of chemical species and kinetic mechanisms can be improved by spectroscopic measurements. In particular, the PCCI combustion was investigated by imaging and spectral measurements of the natural emissivity both in the visible (VIS) and in the near ultraviolet (UV). The detection of the species involved in the combustion process, like OH, HCO, CH, and their relevance on PCCI were analyzed and compared with the data from thermodynamic analysis.

EXPERIMENTAL APPARATUS

OPTICAL SINGLE CYLINDER ENGINE

The optical single-cylinder diesel engine used for combustion diagnostics was equipped with the combustion system architecture and injection system of a four-cylinder standard engine. The transparent single-cylinder engine has been equipped with head and Common Rail (CR) injection system of the four-cylinder, 16 valves, 1.9 l standard production engine. The engine stroke and bore are 92 mm and 85 mm, respectively. An external air compressor has been used to supply pressurized intake air in order to obtain the same in-cylinder conditions of the real multi-cylinder engine and to compensate lower compression ratio, typical of the optical engines. Moreover, the exhaust gas recirculation (EGR) system was deactivated and the variable swirl actuator (VSA) system was managed by an external device. This system consisted of a set of blades mounted in the intake manifold in front of the helical shape intake duct of the engine head. The VSA controlled the swirl motion of the intake air. The high value of the VSA position induces high swirl motion to the intake air. The variable swirl throttle actuator (VSA) system was set to 66%.

The engine lay-out with the experimental apparatus is shown in [Figure 1](#). Moreover, the engine specifications are reported in [Table 1](#). The optical engine utilized a conventionally extended piston with a piston crown window of 46 mm diameter which provided full view of the combustion bowl by locating an appropriate 45° UV-visible fixed mirror inside the extended piston.

CR injection system managed by a fully opened electronic control unit (ECU) fuelled the engine with diesel fuel. The ECU allowed to control the number of injections per cycle, the injection pressure, the injection start, the energizing time that manage the diesel injector as well as the dwell time between two consecutive injections. The injection system specifications are reported in [Table 1](#). On the other hand, the production intake manifold of the engine was modified to set an electronic port fuel injector (PFI) generally used in modern gasoline engines. It was a production one suitable for gasoline and E85 fuel. It was fed by an automotive electrical pump able to reach up to 3.5 bar injection pressure and it was used with pure ethanol fuel. It was applied directly into the non-swirl actuated intake port. [Figure 2](#) reports the intake manifold modified and the PFI injector tip protrusion.

The common rail injection system was controlled by the ECU and the ethanol injector control was managed using a delay unit synchronized with the shaft encoder. The delay unit generated a pulse width for the injection timing and the fuel quantity of the injection event.

Table 1. Engine and injection system specifications

Engine type	4-stroke single cylinder
Bore	8.5 cm
Stroke	9.2 cm
Swept volume	522 cm ³
Combustion bowl	19.7 cm ³
Vol. compression ratio	16.5:1
Diesel Injection system	Common Rail DI
Injector type	Solenoid driven, Minisac nozzle
Number of holes	7
Cone angle of fuel jet axis	148°
Hole diameter	0.141 mm
Rated flow @ 100 bar	440 cm ³ /30s
Ethanol Injection system	PFI
Number of holes	10
Cone angle	14°
Separation angle	22°
Rated flow @ 3bar	202 cm ³ /min

The injection signals were analyzed by means of multichannel acquisition system. The solenoid current that managed the diesel injector was detected through a Hall-effect sensor. Moreover, to acquire the cylinder pressure in motored and fired condition, a piezoelectric pressure transducer was set in the glow plug seat of the engine head.

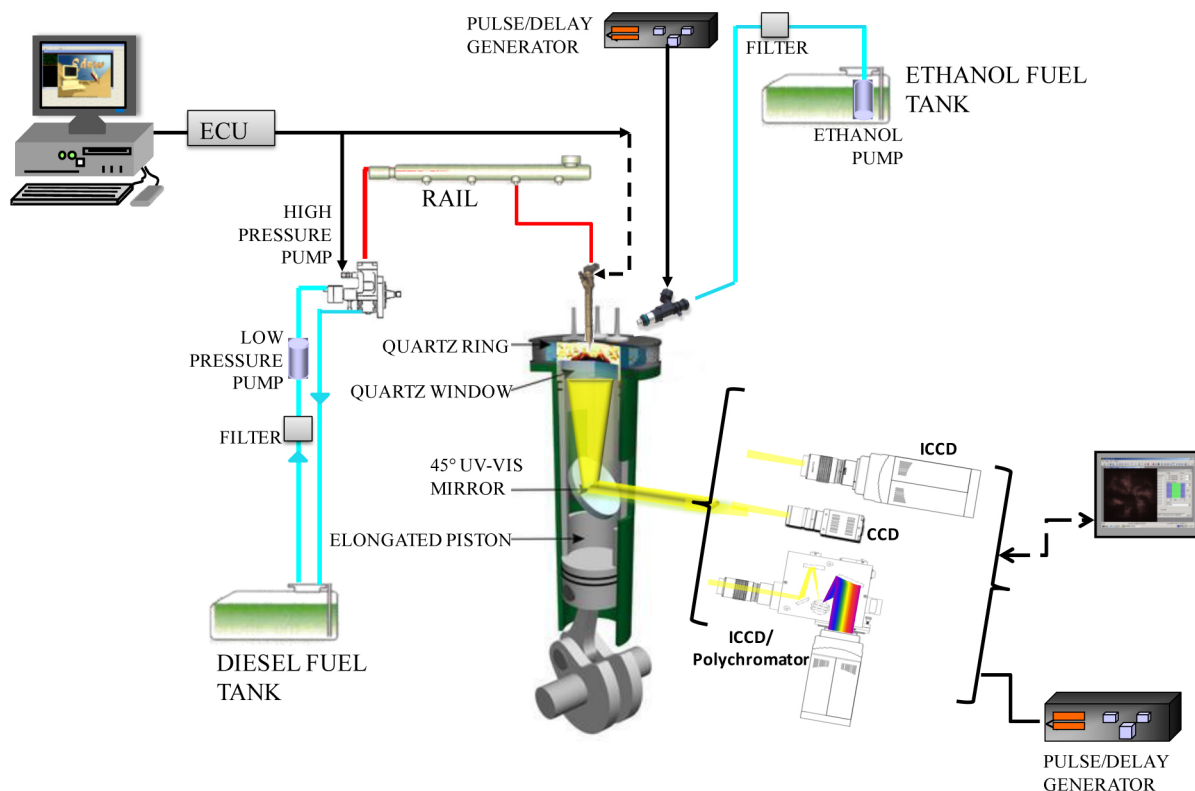


Figure 1. Optical single cylinder engine experimental setup

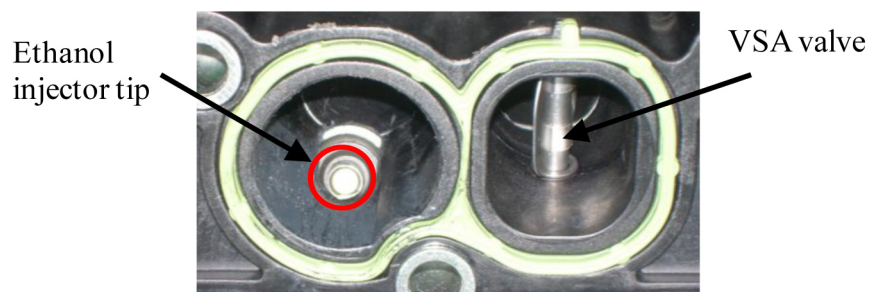


Figure 2. Modified intake manifold allowing PFI bio-ethanol injection

For each operating condition investigated, the cylinder pressure, and the drive injectors current signals were digitalized and recorded at 0.5° crank angle (ca) increments. The average in-cylinder pressure was calculated from 200 consecutive combustion cycles. The heat release rate was calculated from the averaged pressure data using the typical first law and the perfect gas analysis [10].

In order to realize a kinetically controlled combustion process it was necessary to increase the ignition delay of the diesel fuel that is highly reactivity. Bio-ethanol mixed with diesel fuel allowed reaching this objective and improve further the combustion process in terms of performance and emission. In particular, as it reports in Table 2, it is low reactive fuel; it

has high oxygen content and free aromatics compounds, and has a smaller lower heating value (LHV) and density than diesel fuel. Finally, the larger research octane number (RON), with respect to gasoline, could permit to operate both with high compression ratio and high boost.

Table 2. Chemical and physical properties for bio-ethanol and diesel fuel

Fuel property	Bio-ethanol	Diesel
Formula	C ₂ H ₅ OH	C _n H _m O _r
Molecular weight [g/mol]	46,07	233
Carbon [mass%]	52,2	85,2
Hydrogen [mass%]	13,1	13
Oxygen [mass%]	34,7	1.45
Density, kg/l, 15/15 °C	0,79	0,83
Boiling point, °C	78	180-360
Vapor pres., kPa at 38 °C	15,9	53,3
Specific heat, kJkg ⁻¹ K ⁻¹	2,4	2
Viscosity, mPa s at 20 °C	1,19	76
Low. heating val., 10 ³ kJ/l	21,1	35,66
Autoignition temp., °C	423	270
Research octane number	108,6	-
Motor octane	92	-
(R+M)/2	100	-
Cetane Number	-	51.8
Flammability lim., Vol %	4,3/19	0,6/6,5
Water Tolerance, Vol %	Compl.miscible	Negligible
Stoichiometric air/fuel	9	14,5
Aromatic, Vol%	0	11
Carbonyl [ppm] as C-O	567	-
Carbonyl [ppm] as acetone	1117	-
Carbonyl [ppm] as acetaldehyde	893	-
Sulphur [mg/kg]	< 0.8	10
Copper [mg/kg]	<0.1	-

ENGINE OPERATING CONDITIONS

The engine operating conditions investigated are reported in Table 3. The diesel fuel was injected by means of single main injection. For all the strategies investigated, the injection starts at 6° ca before top dead center (BTDC), has duration of 450 μs and injection pressure of 800 bar. The bio-ethanol injections were performed in the intake manifold at 3.5 bar when both the intake and exhaust valves were closed. Thus, the ethanol had sufficient time to evaporate and to mix well with the intake air. The ethanol strategies were managed increasing the crank angle duration from 0° up to 70° ca with a step of 10°ca. Ethanol injection duration was not used longer than 70° ca because it inhibits the combustion. All the tests were performed at engine speed of 1500 rpm and the engine ran in continuous way.

OPTICAL SETUP

In Figure 1 the optical diagnostics tools used to investigate the dual-fuel PCCI combustion process are reported. They are set in front of a 45° UV-VIS mirror. Spectroscopic measurements were carried out by means of the spectrograph and a gated intensified CCD (ICCD) camera. The ICCD had high sensitivity in the UV-VIS range, (512 × 512 pixels) with

24×24 μm² pixels. The UV-VIS flame emission was collected and focused on the entrance slit of a spectrograph through an UV objective (Nikon 78 mm f/3.8). Spectrograph had 15 cm focal length, f/4 luminous, and was equipped with a grating of 300 grooves/mm, blazed at 300 nm, with a dispersion of 3.1 nm/mm. An entrance slit width of 100 μm was used. The spectral image formed on the spectrograph exit plane was matched with the ICCD camera. The spectrometer's field of view was due to the magnification of the optics, the slit height (1 mm) and variable width of spectrograph, so as the ICCD pixel size. Data were detected with the spectrograph placed at a central working wavelength of 350 nm and with the intensifier-gate duration of 55 μs in order to have a good accuracy in the timing of the combustion onset. The spectrograph-ICCD calibration was made by Mercury-vapor, Deuterium, and Tungsten lamp. All spectral measurements presented are ensemble-averaged over 50 cycles to improve signal to noise ratio especially at low luminosity condition. Table 4 shows the prominent spectral peaks of intermediates and products of combustion in the UV and VIS regions [11].

Figure 3 reports the combustion chamber with the injector in centre, the intake (I) and exhaust (O) valves, and the investigated area by spectroscopic analysis associated to the 100 μm entrance slit. The area was divided into twenty region of interest. Each one is constituted by 25×20 pixels and has an area of 5.1×4.6 mm². The spectra obtained in location named A, B, C, D, and E, are reported in the paper. They were chosen in order to investigate the effect of diesel injection, the valve opening and the mixture with ethanol.

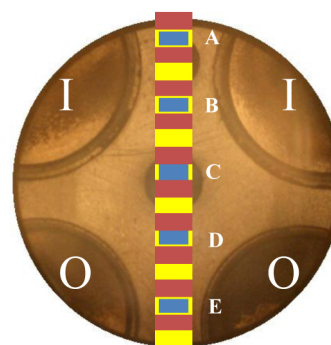


Figure 3. Combustion chamber locations investigated by spectroscopic measurements

In order to better investigate also the spatial distribution and temporal evolutions of the UV-VIS emission light and of the typical combustion species previously detected by the spectroscopic measurements, images were recorded with ICCD camera. In particular, the OH and HCO spatial distributions were investigated applying in front of the objective lens two band pass filters at 310 nm and 350 nm