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Spectroscopic analysis of the phases of premixed combustion in a compression ignition engine fuelled with diesel and ethanol

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HIGHLIGHTS

- Spectroscopic measurements and 2D UV–VIS digital imaging in optical-access Euro 5 CR diesel engine.
- Study of dual operation in the engine fuelled with ethanol in intake manifold and diesel into the cylinder.
- Combustion mode moves from two-stage to three-stage increasing the premixed ratio.
- Intermediate heat release was affected by the amounts of injected ethanol and diesel as well as the SOI of diesel fuel.

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ABSTRACT

The premixed charge compression ignition (PCCI) combustion represents a possible solution for decreasing the pollution with respect to diesel engine, while maintaining the efficiency rate at values that are comparable, and in some cases higher, than those of a diesel engine. This paper investigates the operation of an optical-access compression ignition engine (bore: 82 mm, stroke: 90 mm) running at PCCI combustion with neat bio-ethanol and European commercial diesel fuel injected in the intake manifold and into the cylinder, respectively. In its original configuration, the engine burned diesel and this case was used as reference of compression ignition combustion. Then, different amounts of bio-ethanol were injected varying the energizing time of the injector set in the intake manifold. This allowed to create PCCI combustion with high levels of pre-combustion mixing, and to ensure low equivalence ratio and low flame temperatures too. Moreover, both the amount and the start of diesel injection was varied to investigate their effects on the several combustion phases. UV–Visible imaging and spectroscopic measurements were performed in the engine and the autoignition of the charge, the combustion process and the chemical species involved were detected and analysed. In particular, optical diagnostics allowed to observe how the mixture burned: no luminous flame emission in the visible range was recorded; while in the ultraviolet wavelength range numerous species, like HCO, HCOH, OH, and CO and others were detected. Varying the in-cylinder premixed ratio the combustion retarded and the rate of heat release passed from single to three-phase premixed combustion, so revealing a phase due to intermediate temperature reactions. The same behavior was observed varying the start of injection and the quantity of diesel that affected the premixed ratio. Spectroscopic measurements revealed that during the intermediate temperature heat release large amount of OH radical governed the start of combustion of the charge. It was also observed that the preignition combustion was mainly due to the stratified mixing of the diesel fuel close to the bowl wall. Finally the presence of OH radical was monitored for the whole combustion process.

1. Introduction

Nowadays, advanced combustion strategies represent the best solution to reduce pollutant emissions keeping constant the performance of commercial diesel engines. Among the advanced combustion modes, premixed charge compression ignition (PCCI) and homogeneous charge compression ignition (HCCI) have shown to be promising strategies to achieve these goals [1–4]. In particular, in PCCI combustion there are high levels of pre-combustion mixing

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Abbreviations: ATDC, after top dead center; BTDC, before top dead center; ca, crank angle; COV, coefficient of variation; CR, common rail; DI, direct injection; DOI, duration of injection; ECU, electronic control unit; EGR, exhaust gas recirculation; ET, energizing timing; HTHR, high temperature heat release; ICCD, intensified charge coupled device; ITHR, intermediate temperature heat release; LHV, low heating value; PCCI, premixed charge compression ignition; PFI, port fuel injector; ROHR, rate of heat release; RON, research octane number; r_p, premixed ratio; SOC, start of combustion; SOI, start of injection; TDC, top dead center; UV, ultraviolet; VIS, visible; VSA, variable swirl actuator.

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that ensure a low equivalence ratio and low flame temperatures, so that both nitrogen oxides (NO_x) and particulate matter (PM) emissions are lower. The high level of pre-combustion mixing results in a primary kinetics controlled combustion process. In order to get to this circumstance in a compression ignition engine, it is necessary to increase the ignition delay of the diesel fuel that is highly reactive [5–7]. Generally, PCCI combustion was obtained in light and heavy duty diesel engines using gasoline and diesel fuel mixture; moreover, several papers analyzed the possibility to use biofuels too [5–14]. Ethanol and n-butanol feed the engine as un-reactive fuel to prepare the pre-mixing charge, and diesel and biodiesel as the high cetane number fuel for the charge ignition. The easiest method ethanol could be used with diesel fuel is in the form of solution [8–10]. However, bio-ethanol is not soluble or has very limited solubility in diesel fuel. The solubility of the bio-ethanol and diesel mixture depends on the hydrocarbon composition of the diesel fuel, water content of the blends, and environment temperature [15–16]. Therefore, the ethanol–diesel solutions are reduced to small percentages. In order to solve the problems of phase separation small amounts of additives were used. As additive, biodiesel fuels are very good, allowing to overcome the solubility problems and improving the cetane number of the blended fuels [11]. On the other hand, some researchers proceeded by injecting ethanol in the intake manifold in order to allow the use of high percentages of ethanol, while the diesel was injected directly into the cylinder [5–7,12–14]. However, this method required a second port fuel injection system and its control. Probably, this is the best solution available now. Nevertheless, it is necessary to phase the combustion due to the different autoignition characteristics of the adopted fuels. In fact, if the charge cooling is greater than the exothermic reactions of the autoignition event the combustion could become erratic with misfire or partial-burn cycles. However, the effect of ethanol addition to the intake air to increase the in-cylinder premixed charge and the ethanol effects on the combustion in a compression ignition engine are not well known. Even if the inhibitory effects of ethanol on the autoignition of diesel fuel was studied by other authors [11–14], no information was provided about the species involved in the process and on the several phases of combustion that derived by the retarded reactions.

Generally, within the engine, oxidized hydrocarbon can show two different types of behavior depending on the pressure and temperature of the mixture [17]. In particular, at 300/400 °C one or more combustion waves often appear, accompanied by faint blue light emission [18]. These are called cool flames. Depending on the conditions and the fuel, the cool flame may be followed by a hot flame or high-temperature explosion where the reaction accelerates rapidly after ignition. This is called two-stage ignition. Moreover, homogeneous charge compression ignition (HCCI) combustion of diesel-like fuels shows a peculiar two-stage heat release [3]. The first stage of the heat release curve is associated to low temperature kinetic reactions, and the time delay between the first and main heat releases is attributed to the "negative temperature coefficient (NTC) regime" which occurs between the two heat release stages. In this NTC regime, the overall reaction rate decreases though the in-cylinder temperature increases, which leads to a lower reactivity of the system. Heat release from low temperature reaction relates to octane number of fuels. The lower is the octane number, the more obvious is the heat release of low temperature reaction [3]. Sjoberg et al. carried out several studies about the effect of fuel, intake temperature, pressure and other parameters on ignition delay of HCCI combustion [19,20]. In particular, their engine operated with PRF80 (primary reference fuel with 80% iso-octane and 20% n-heptane) which shows two-stage ignition with low-temperature heat release, and gasoline and ethanol as representative of single stage ignition fuel [20]. They observed for these fuels intermediate-temperature heat release (ITHR) just before the hot-ignition point. However, ethanol did not produce low temperature heat release (LTHR) and much less ITHR than the other tested fuels. They concluded that ethanol is a true single-stage ignition fuel. Furthermore, Xingcai et al. [21] analyzing the autoignition of ethanol/n-heptane blends fuels found out that, at a specific indicated mean effective pressure (IMEP), the ignition timing of the cool flame is delayed substantially and the initial temperature corresponding to the cool flame reaction gradually increases with the introduction of the ethanol addition. The most important reason is the super high octane number of ethanol fuel, which leads directly to the ignition delay of the ethanol/diesel blend fuels. The other reason can be due to the much higher latent heat of evaporation of ethanol fuel. This leads to a lower initial temperature of the compression stroke [21]. Moreover, they found out that for a specific partial equivalence ratio of n-heptane, ignition timing of the cool flame delays obviously with the introduction of the ethanol addition. This means that, for dual-fuel system or blend fuel system, the HCCI ignition timing is not only dominated by the fuel with higher cetane number, but is also influenced by the physical and chemical properties of two fuels [21]. In the past activities the authors had also evidence of two-stage autoignition process burning a homogenous mixture of diesel and air in compression ignition engine [22]. In particular, HCCI combustion mode was obtained by means of five early injections with both high pressure and short duration of the injections to avoid the cylinder wall impingement. The rate of heat release for HCCI mode shows two well identified peaks not correlated with the injections. The first is characteristic of low temperature reactions; the second one is due to the development of high temperature reactions. The combustion occurs exclusively in a premixed mode and its duration is considerably short with respect to a diesel common rail (CR) standard combustion [22]. No delay and NTC was observed between the low and high temperature reactions. Also for low temperature combustion obtained by means of one and late injection and large amount of gas recirculating from the exhaust duct, the authors observed a two stage ignition, even if the low temperature heat release was very short [23].

In this work, dual fuel PCCI operation mode was obtained by adding bio-ethanol, which is a relatively un-reactive fuel, to the intake air entering the engine by means of an injector for port fuel injection (PFI) application. Moreover, European commercial diesel fuel was injected directly into the cylinder by means of production common rail (CR) injection system. The engine used was a single cylinder optical engine equipped with a commercial head of passenger car diesel engine. In its original configuration, the engine burned diesel and this case was used as reference of compression ignition combustion. Several injection strategies were tested varying the premixed level of the in-cylinder reacting charge adding ethanol in the intake. Moreover, both the amount and the start of diesel injection were varied to investigate their effects on the several combustion phases. Since this combustion is a chemical-reaction governed process, the knowledge of chemical species and kinetic mechanisms must be improved. Advanced optical diagnostics like flame emission spectroscopy, chemiluminescence, and 2D digital imaging both in ultraviolet (UV) and in visible (VIS) wavelength ranges were carried out. The detection of OH radical involved in the combustion process and its relevance on PCCI were analyzed and compared with the data from thermodynamic analysis.

2. Methodology

2.1. Optical single cylinder engine

The optical-access single-cylinder diesel engine used for combustion diagnostics was equipped with the combustion system