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Simulation of HCCI combustion in air-cooled off-road engines fuelled with diesel and biodiesel

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ABSTRACT

The present work describes the elaboration of a predictive tool consisting on a phenomenological multi-zone model, applicable to the simulation of HCCI combustion of both diesel and biodiesel fuels. The mentioned predictive tool is created with the aim to be applied in the future to perform engine characterization during both pre-design and post-design stages. The methodology applied to obtain the proposed predictive model is based on the generation of an analytical mechanism that, given a set of regression variables representing the engine operative conditions, provides the user with the optimal figures for the scaling coefficients needed to particularize both the ignition delay and the heat release rate functional laws, which rule the combustion development in the proposed multi-zone model for HCCI engines. The validation of the proposed predictive multi-zone model consists on the comparison between chamber pressure curve derived from the simulations and experimental data based on a DEUTZ FL1 906 unit modified in order to allow HCCI combustion operation mode using diesel EN590 and rapeseed biodiesel. Finally, evidences of the capabilities of the proposed model to be used as a predictive tool applicable to the analysis of off-road engines under HCCI conditions are provided, consisting in the characterization and optimization of the operational maps related to both Brake Specific Fuel Consumption and NOx emissions.

1. Introduction

According to the International Energy Agency (IEA) [1], fuel consumption will increase steadily over the period to 2040, to help meet a one-third rise in global energy demand. However, the same source states that global emissions of particulate matter (PM), sulphur dioxide (SO_2) and nitrogen oxides (NOx) are projected to fall over the same period, as a consequence of energy and climate regulations. Table 1 shows the variations (related to 2016), by some regions, derived from the IEA projections by 2040 regarding SO_2, NOx and PM.

As a result of the increasingly demanding legislation in force in most of the industrialized countries, the Internal Combustion (IC) engine industry is facing significant challenges, among which are both the reduction of pollutant emissions and the increase of thermal efficiency [2]. The combination of the previous demands with the widespread deployment of the IC engines derives in the imperative necessity of identifying continuous improvement measures, together with the optimization of the current production costs. Between the strategies considered by the IC engine sector it is noteworthy the search of alternative technologies to Spark Ignition (SI) and Compression Ignition (CI) conventional combustion modes, being the Homogeneous Charge Compression Ignition (HCCI) combustion one of the most promising options [3], even though several challenges still need to be addressed, jointly with other similar combustion modes such as Premixed Charge Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI) [4].

HCCI combustion is typically characterized by a lean mixture between air and fuel, reaching a significant degree of homogeneity before the start of combustion, which happens as an auto-ignition, without the participation of external agents. Furthermore, this auto-ignition

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Table 1
SO_2, NOx and PM emissions variations (related to 2016) as per IEA projections by 2040 [1].

Region	SO_2	NOx	PM
United States	−50%	−50%	−33%
European Union	−47%	−55%	−20%
China	−30%	−30%	−40%
India	+10%	+10%	+7%
Southeast Asia	+45%	+45%	−13%

starts simultaneously in different points of the combustion chamber, randomly located, without the presence of a flame front according to the results derived from optical analysis [5,6]. The previous characteristics make possible HCCI combustion to develop a very fast Heat Release Rate (HRR), with a small variation of volume. Additionally, HCCI combustion is compatible with relatively high compression ratios, similarly to CI engines, due to the low risk of knocking. Other similarity with CI engines is the lack of relevant mechanical losses related to pumping loop. Finally, HCCI combustion is possible with wide-ranging variety of fuels [7], differently from conventional SI and CI engines.

Some of the previous mentioned characteristics, such as the fast combustion, the high compression ratio and the minimization of the mechanical losses, allow HCCI combustion to reach relatively high thermal efficiencies, comparable to the conventional CI engines [8,9]. Moreover, the significant degree of homogeneity needed to perform HCCI combustion avoids the existence of rich areas, which means the practically absence of particulate matter, equivalently to current SI engines. Finally, the non-existence of very high temperature areas, as a result of the mentioned homogeneous charge, lean mixture and lack of flame front, results in a significant cutback of the nitrogen oxides (NOx). The referred advantages provide HCCI combustion with a potential attractive compared to conventional SI and CI engines.

However, HCCI combustion drawbacks are significant, limiting its current commercial implementation. The main disadvantages consist on the difficulties related to the control of the start of combustion, since it is not triggered by external agents [10], and the limitations to the operation range in HCCI mode. On one hand, low loads derive in high emissions of unburned hydrocarbons (UHC) and carbon monoxide (CO) [8], due to the lack of thermal energy to promote the complete combustion of fuel [11]. Apart from incomplete combustions, low loads are related to slow heat release rates, with significant variations of volume, which penalize thermal efficiency. On the other hand, high loads in engines under HCCI operation mode are characterized by significant emissions of NOx, due to the high temperatures derived from fast heat release, which are accompanied by an undesired advance in the start of combustion, high pressure gradients, noise and knocking [12–14], all of them representing a risk for the mechanical integrity of the IC engines. Finally, cold start difficulties are also referred as one of the typical disadvantage of HCCI combustion, since the chamber walls are cold, which maximizes the heat losses from the air-fuel mixture, preventing auto-ignition to happen.

Focussing on the particular research necessities related to the HCCI combustion three main topics are typically referred: firstly, optical analysis to provide a better understanding about the phenomena that take place within the combustion chamber, secondly, numerical modelling to perform high quality simulations oriented to identify the parameters influencing the mentioned phenomena and, finally, control systems to optimize HCCI combustion performance in terms of power and pollutant emissions [15]. Intrinsically related to the second topic, numerical modelling, the present work describes the elaboration of a predictive tool consisting on a phenomenological multi-zone model, applicable to the simulation of HCCI combustion of both diesel and biodiesel fuels. Multi-zone models have demonstrated, after proper calibration, the capability of generating accurate predictions for IC engines, while not demanding significant amounts of resources. Based on the proposed model flexibility and low computational cost, additionally to the contribution to the simulation field, the work developed by the authors is created with the aim to be applied in the future to the development and testing of new improvement strategies oriented to overcome HCCI combustion current limitations, also mentioned previously as a major research demand.

2. Material and methods

2.1. Experimental methodology

The empirical basis of this work has been developed using a DEUTZ FL1 906 unit, a single cylinder, four-stroke, naturally aspirated, direct injection diesel engine, whose main rated characteristics are shown in Table 2. However, the unit configuration was modified in order to allow HCCI combustion operation mode:

- Introduction of an external Exhaust Gas Recirculation (EGR) system. Recirculated combustion gases were cooled down to ambient temperature before mixing with the fresh air flow not to promote combustion advancement of diesel and similar fuels with high cetane number, as a consequence of the so-called thermal effect of external EGR.
- Modification of the Start Of Injection (SOI) and Compression Ratio (CR). Two different configurations (early HCCI and late HCCI) were used experimentally, as described by Jiménez at al [16]. Early HCCI configuration was characterized by CR of 15:1 and SOI 45° BTDC, while CR of 18.4:1 and SOI 10° BTDC was used in late HCCI configuration. Although less attractive in terms of efficiency, late HCCI configuration was required in order to allow the use of biodiesel in HCCI combustion mode. Otherwise, mechanical damages happen even after a few hours of operation as a consequence of the physical–chemical properties of biodiesel, which hinder the vaporization of liquid fuel and lead to fuel deposition in cylinder walls. Summarizing, late HCCI configuration presented the only advantage of allowing the continuous use of biodiesel, not possible with the early HCCI configuration. Based on this fact, no switching mode between both configurations was considered.
- Optimization of the bowl-in-piston geometry as a measure to enhance turbulent mixing. The achievement of high swirl ratios before the start of combustion was an essential requirement to satisfactorily perform with the late HCCI setup [17].
- Increase of injection maximum pressure up to 650 bar, which leads to shorter injection periods, faster fuel evaporation and more homogeneous fuel-air mixtures.

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