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Effects of piston bowl geometry on Reactivity Controlled Compression Ignition heat transfer and combustion losses at different engine loads

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A B S T R A C T

This work investigates the effects of the piston bowl geometry on RCCI (Reactivity Controlled Compression Ignition) heat transfer and combustion losses and its repercussion on the engine efficiency. For this purpose, three piston geometries with compression ratio 14.4:1 have been studied and compared by means of computational modeling. In addition, the engine operating conditions proposed at low, medium and high load were also validated experimentally in a heavy-duty single-cylinder engine adapted for dual fuel operation. The engine speed was kept constant at 1200 rev/min during the research.

Results suggest that heat flux through the piston surface represent the major portion of the heat transfer energy. Thus, the comparison of the three geometries demonstrates that reduced piston surface area and reduced charge motion, are the key factors to improve the gross indicated efficiency over the different engine loads. Moreover, it is found that a shallow piston geometry with a smooth transition from the center to the squish region, with a 16% reduced surface area, strongly improves the gross work at low load. However, this gain diminishes due to increased combustion losses as engine load increases. Finally, an intermediate geometry was confirmed as the best balanced piston geometry for RCCI operation over the three different loads.

1. Introduction

The stringent regulations introduced around the world to limit the pollutant emissions in ICE (internal combustion engines) present a major challenge for the engine research community. In spite of its efficiency, conventional mixing-controlled diesel combustion in CI diesel engines requires complex and costly exhaust after-treatment systems to reach the NO_x and soot limitation values proposed in the current regulations, such as EURO VI. Specifically, the rich local equivalences ratios and the high temperatures achieved during the CDC (conventional diesel combustion) as well as the oxygen availability in the outside of the spray plume results in an unacceptable emissions. Additionally to the complexity of the aftertreatment systems, the use of DPF (to reduce soot emissions) and LNT or SCR (to minimize NO_x emissions) requires a periodically regeneration (operating rich) or the introduction of a reducing agent, which penalizes the fuel consumption. Thus, in order to reduce after-treatment costs and fuel consumption it is necessary to avoid the generation of these pollutants in the focus of the emission, i.e. during the combustion development.

Many new compression ignition combustion strategies have been proposed to simultaneously improve the engine efficiency while reducing the NO_x and soot emission levels under the regulation limits [1,2]. The more promising combustion strategies are the well-known LTC (low temperature combustion) strategies. A widely investigated combustion strategy is HCCI (homogeneous charge compression ignition), which produces virtually no soot or NO_x emissions while maintaining high efficiency [3–5]. However, this combustion process presents new challenges with regard to combustion control and engine stress. Due to the rapid heat release, steep pressure gradients occur so that the process has been limited to use within the partial load range [6]. On this regard, Bessonette et al. [7] suggested that different in-cylinder reactivity is required for the proper HCCI operation under different operating conditions. Specifically, high cetane fuels are required at low load and a low cetane fuel is needed at medium-high load.

With the aim of improving the HCCI shortcomings in terms of controllability and knocking, the use of fuels with lower reactivity than diesel fuel (gasoline-like fuels) under PPC (Partially Premixed Combustion) strategies has been widely investigated [8–10]. The

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investigations confirmed gasoline PPC as a promising method to control the heat release rate providing a reduction in NO_x and soot emissions [11,12]. Thus, by injecting the fuel later in the engine cycle than in HCCI strategy, the air-fuel mixing degree is reduced and therefore higher control on the ignition delay as well as the combustion duration is achieved. Additionally, the use of gasoline fuel provides more flexibility to achieve the required extra mixing time at medium-high loads [13]. However, the concept has demonstrated difficulties at low load conditions [14,15] using gasoline with ON (octane number) greater than 90. With the aim of improving the PPC cycle-to-cycle control at low loads using high ON gasolines, PPC spark assisted concept has been studied [16,17]. It has been demonstrated that the spark assistance provides temporal and spatial control over the combustion process [18], however the high local reactivity required between the spark plug electrodes at the start of spark timing and the flame propagation process result in an unacceptable NO_x and soot emissions [19]. In this sense, the double injection strategy applied to the PPC spark assisted concept has been confirmed as a suitable strategy to improve the unburned HC and CO emissions, but still do not solve the unacceptable NO_x and soot emission levels [20,21].

Recent experimental and simulated studies demonstrate that RCCI (Reactivity Controlled Compression Ignition) combustion is a more promising LTC technique than HCCI and PPC [22,23,24]. RCCI concept is a partially premixed combustion strategy based on dual-fuel operation, which allows using several types of high and low reactivity fuel combinations [25,26]. To delivery both fuels separate injection systems for the low reactivity and high reactivity fuel are used, being port fuel injected (PFI) and direct injected (DI) respectively. Thus, a flexible operation over a wide operating range is possible by modifying both, the low reactivity fuel percentage in the blend and the direct injection timing. The variation of these engine settings provides the required in-cylinder equivalence ratio and reactivity (i.e. octane number) stratification. According to previous studies [27], in which RCCI concept was evaluated from 25% to full load using the stock piston bowl geometry ($CR = 14.4:1$), RCCI provides very low NO_x and soot compared to conventional Diesel combustion (CDC) reference cases. In addition, a benefit in fuel consumption from low to medium load compared to CDC was also appreciated. However, this advantage was not confirmed for higher loads. In spite of the benefits of RCCI concept in terms of fuel consumption, a worse combustion efficiency than CDC was observed, with values around 97% at low load conditions. In this sense, an experimental investigation combined with computational modeling [28], demonstrated that it is possible to improve the low load combustion efficiency to values above 98% by combining the effects of in-cylinder gas temperature and oxygen concentration respectively with the in-cylinder fuel blending ratio. Moreover, it was also confirmed that a certain level of unburned HC and CO remained unaffected by the engine settings. Finally, recent investigations analyzed their dependency on geometric parameters such as crevices and squish volumes, which difficult the combustion progression resulting in incomplete combustion [29]. In addition, it was identified that RCCI concept also offers an interesting potential for improving fuel consumption by lowering wall heat transfer. Thus, the main objective of the present work is to evaluate the influence of the piston bowl geometry on RCCI heat transfer and combustion losses at low, medium and high engine loads and its effects on engine efficiency. For this purpose, additionally to the stock geometry, two piston bowl geometries has been defined and evaluated by means of CFD calculations to obtain further insight in RCCI heat transfer and unburned products (CO and HC) formation and destruction during combustion. Moreover, the three piston bowl geometries studied were machined to validate the theoretical findings in a heavy-duty research diesel engine at the three engine loads.

2. Experimental facilities and processing tools

2.1. Test cell and engine description

A single cylinder, HD diesel engine representative of commercial truck engine, has been used for all experiments in this study. The major difference to the standard unit production is the hydraulic VVA system, which conferred great flexibility during the research. In particular, the valve timing, duration and lift can be electronically controlled for each valve during the engine tests. Thus, an adapted cylinder head to include a dedicated oil circuit is required. Detailed specifications of the engine are given in Table 1.

The engine was installed in a fully instrumented test cell, with all the auxiliary facilities required for its operation and control, as it is illustrated in Fig. 1.

Moreover, to achieve stable intake air conditions, a screw compressor supplied the required boost pressure before passing through an air dryer. The air pressure was adjusted within the intake settling chamber, while the intake temperature was controlled in the intake manifold after mixing with the EGR flow. The exhaust backpressure produced by the turbine in the real engine was replicated by means of a valve placed in the exhaust system, controlling the pressure in the exhaust settling chamber. Low pressure EGR was produced taking exhaust gases from the exhaust settling chamber. The determination of the EGR rate was carried out using the experimental measurement of intake and exhaust CO_2 concentration. The concentrations of NO_x, CO, unburned HC, intake and exhaust CO_2, and O_2 were analyzed with a five gas Horiba MEXA-7100 DEGR analyzer bench by averaging 40 s after attaining steady state operation. Smoke emission were measured with an AVL 415S Smoke Meter and averaged between three samples of a 1 L volume each with paper-saving mode off, providing results directly in FSN (Filter Smoke Number) units. PM measurements of FSN were transformed into specific emissions (g/kWh) by means of the factory AVL calibration.

2.2. Piston bowl geometries

As identified in the introduction section, the potential areas for RCCI optimization are the combustion efficiency and fuel consumption. Thus, in order to reduce the unburned HC and CO within the squish region and also to mitigate the wall heat transfer, a series of bowl geometries were designed and evaluated by means of computational calculations and experimental tests.

The first geometry was named as steeped and maintains the stock piston central geometry with a modified transition to the squish region, as shown in Fig. 2. The aim of this geometry is to modify the squish flow in order to facilitate the unburned products

Table 1
Single cylinder engine specifications.

Engine type	Single cylinder, 4 St cycle, DI
Bore × Stroke [mm]	123 × 152
Connecting rod length [mm]	225
Displacement [L]	1.806
Geometric compression ratio [–]	14.4:1
Bowl Type	Open crater
Number of Valves	4
IVO	375 CAD aTDC
IVC	535 CAD aTDC
EVO	147 CAD aTDC
EVC	347 CAD aTDC