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Research Paper

Gaseous emissions and particle size distribution of dual-mode dual-fuel diesel-gasoline concept from low to full load

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HIGHLIGHTS

- Dual-mode dual-fuel arises as an evolution of low temperature combustion strategies.
- No relation is observed between smoke and particle matter at dual-mode dual-fuel.
- Higher number of particles obtained for dual-mode dual-fuel than conventional diesel.
- Nucleation moves to accumulation mode as engine load increases at dual-mode dual-fuel.
- Mainly diffusive strategy shows clear relation between smoke and particle matter.

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ABSTRACT

Low temperature combustion concepts are in focus of study nowadays as a method to avoid the NOx-soot trade-off existing with conventional diesel combustion. One of the most promising strategy is known as reactivity controlled compression ignition because of its high thermal efficiency and the ultra-low nitrogen oxides and soot emissions. However, this concept presents several challenges such as the high levels of carbon monoxide and unburned hydrocarbons promoted at low load and unacceptable levels of pressure rise rate at high load. Therefore, to mitigate these shortcomings the dual-mode dual-fuel concept, combining reactivity controlled compression ignition and diffusive dual-fuel diesel-gasoline combustion, has been developed.

Total number of particles is also limited by the emission standards. Previous studies focused in particles emissions carried out by the research community present particle size distribution, composition and mass of the particles on reactivity controlled compression ignition combustion mode. Additional studies were carried out in order to identify the components of these particles, being partially formed of volatiles, and reflects that particles are smaller than at conventional diesel combustion, presenting higher number of particles from nucleation mode than from accumulation mode.

Dual-Mode Dual-Fuel concept may present a different behavior for particle distribution with respect to the conventional diesel combustion or the traditional low temperature concepts due to the nature of the particles. The objective of the present study is to measure the particle size distribution as well as gaseous emissions of this new Dual-Mode Dual-Fuel concept from low load to full load for a representative engine speed of 1200 rpm.

Main results of this study suggest that Dual-Mode Dual-Fuel concept promotes higher quantity of particles than conventional diesel combustion despite of providing less smoke. In addition, nucleation mode particles dominate the particle size distribution for the new combustion concept at low load and moves towards accumulation mode domination at full load.

Abbreviations: AIM, Aerosol Instrument Manager; aTDC, after top dead center; CAD, crank angle degree; CA10, crank angle at 10% mass fraction burned; CA50, crank angle at 50% mass fraction burned; CA90, crank angle at 90% mass fraction burned; CDC, conventional diesel combustion; CI, compression ignition; CO, carbon monoxide; CPC, condensation particle counter; CR, compression ratio; DI, direct injection; DMA, Differential Mobility Analyzer; DMDF, dual mode dual fuel; ECU, engine control unit; EGR, exhaust gas recirculation; EOI, end of injection; EU, European Union; EVO, exhaust valve open; GF, gasoline fraction; FSN, filter smoke number; uHC, unburned hydro carbons; HCCI, homogeneous charge compression ignition; IMEP, indicated mean effective pressure; IVC, intake valve close; IVO, intake valve open; LHV, lower heating value; LTC, low temperature combustion; MON, motor octane number; OEM, original equipment manufacturer; ON, octane number; PCCI, partially charged compression ignition; PFI, port fuel injection; PPC, partially premixed charge; PRR, pressure rise rate; PSD, particle size distribution; RCCI, reactivity controlled compression ignition; RoHR, rate of heat release; RON, research octane number; SCE, single cylinder engine; SMPS, scanning mobility particle sizer; SOC, start of combustion; SOI, start of injection; TDC, top dead center.

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1. Introduction

High thermal efficiency in reciprocating engines is one of the targets for the engine manufacturers. Compression ignition (CI) engines provide high thermal efficiency as well as low fuel consumption. Diesel fueled engines have been deeply investigates by the research community [1,2]. Despite the benefits of the conventional diesel combustion (CDC) strategy, several well-known challenges are still persistent due to the mixture stratification [3,4]. The trade-off between nitrogen oxides (NOx) and soot impossibilities the reduction of both emission pollutants simultaneously. In order to meet current emissions regulations such as EURO VI, engine manufacturers have developed aftertreatment systems which drastically reduce theses emissions. Aftertreatment elements imply an increase in the engine cost and operational costs along the engine life.

In order to solve the challenges of the diesel fueled engines, several new compression ignition combustion strategies have been proposed to reduced NOx and soot simultaneously while thermal efficiency is improved [5,6]. Low temperature combustion (LTC) strategies are the most promising combustion modes to avoid the trade-off between NOx and soot [7]. In this sense, homogeneous charge compression ignition (HCCI) virtually avoids any NOx and soot formation [8]. On the other hand, new challenges appear such as pressure rise rate due to the rapid heat release, which limits the concept to the partial load range [9]. Bessonette et al. [10] proposed to use different in-cylinder reactivity with the aim of improving the HCCI operation on the engine. High engine load requires low cetane number and low load requires high cetane number. Following this guideline and trying to face the challenges presented by the CDC mode and discovered at the LTC strategies, the use of low cetane number (gasoline-like fuels) was extended in strategies such as Partially Premixed combustion (PPC) [11]. Investigations suggest that PPC strategy is better method to control the heat release and, at the same time, maintains the benefits of the LTC strategies with low levels of NOx and soot emissions. By contrast, this concept presents difficulties at low load when a higher than 90 octane number (ON) is used [12]. PPC concept was deeply studied in order to improve the cycle-to-cycle variation at low loads by adding spark assistance [13]. PPC spark assisted was capable to operate with higher ON. However, the spark plug requires local rich equivalence ratios at the start of the spark timing to promote the flame propagation. As a consequence, NOx and soot emissions were unacceptable [14]. Inagaki et al. [15] used different ignitability fuels in order to control the combustion under PPC mode. Isooctane fuel was supplied by a port fuel injection (PFI) system and diesel fuel was injected by a direct injection (DI) system. Results provided by the study, show low values of NOx and soot emissions while the efficiency was improved (over 50% of gross indicated efficiency). Due to the use of two fuels, the start of the combustion process was possible to be managed by modifying the reactivity of the fuel blend. Kokjohn et al. [16] named this combustion strategy as reactivity controlled compression ignition (RCCI). RCCI presents the potential to overcome the most important challenges observed with the LTC strategies [17]. RCCI has been investigated in order to explore the capabilities of the concept [18] as well as the effect of the mixture reactivity [19,20]. Additional studies regarding the optimal compression ratio [21] or optimum piston design [22–24] were carried out in order to develop a strategy to allow the concept to reach the full engine map [25]. RCCI has demonstrated to be capable to operate between 10% engine load up to 80% engine load respect CDC mode while the NOx emissions were below EURO VI levels [26]. Nonetheless, RCCI also presents some challenges such as excessive levels of carbon monoxide and unburned hydrocarbons and excessive pressure rise rate at full load.

Aimed to extend the dual fuel operation up to full load with a reduced area of high carbon monoxide (CO) and hydrocarbons (HC) emissions the authors proposed the Dual-mode dual- fuel (DMDF) combustion [27]. DMDF combines fully RCCI strategy at low load with dual-fuel combustion strategies as the load is increased by moving diesel injection (from more advanced to more retarded) and, thereby reducing the fuel premixing blend which turns the combustion behavior more diffusive-like. The potential of this concept is found on the optimum control of the combustion allowing to increase the engine load without exceeding the pressure rise rate remaining the thermal efficiency in levels of RCCI operation mode.

Current standard emissions regulation has introduced a new limitation regarding the number of particles and the particle size distribution (PSD). Particles from CI engines are mainly formed by carbon, and particle measurements are usually mass-based. In order to improve the understanding of the particulate matter (PM) emissions from CDC engines, several studies have been performed to obtain the particle size distribution [28,29]. Kittelson et al. [28] described the particle size distribution (PSD) of CDC operation mode as presenting a bimodal shape. Particles are divided in two modes, nucleation mode and accumulation mode. Nucleation mode contains the smaller particles (D < 50 nm) and accumulation mode the larger ones (D > 50 nm). Nucleation mode particles are mainly formed by volatile organic and sulfur compounds, and some studies associate also ashes derived from the oil to this kind of particles [29]. Particles belonging to the accumulation mode provide the most part of the carbonaceous PM emissions. Kittelson et al. [28] stated that nucleation mode particles would represent less than the 20% of the PM mass emissions but may contain up to 90% of the total number of particles. Additional studies by using ethanol-diesel and ethanol-biodiesel blends were carried out by Armas et al. [30,31] and were compared to diesel fueled only. Armas et al. stated that the use of oxygenated fuels provide a reduction in the number and size of the accumulation mode particles while the nuclei mode particles increased maintaining constant the scanning mobility diameter. Considering the total number of particles and the total mean diameter decreased when fuel blends were used.

From the particle matter at RCCI mode standpoint, their speciation results indicate that the high boiling range of diesel hydrocarbons was likely responsible for the particulate matter mass captured on the filter media [32]. Prikhodko et al. [33] found that RCCI was highly dominated by nucleation mode particles. Several studies confirm that RCCI produces lower number of particles amongst other LTC strategies [34,35]. Kolodziej et al. [36] also studied the effects of the diesel proportion and the injection timings in the particle size while operating under RCCI. Zhang et al. [37] stated that LTC have very similar PSD shapes characterized by smaller sized particles. Prikhodko et al. [33] also compared the results of FSN and PM filter mass measurements under RCCI operation mode, showing that RCCI PM is mostly organic carbon with almost no elemental carbon. Despite of having some correlations between FSN measurement and soot mass for premixed-charged compression ignition (PCCI) operation [38], for RCCI is not possible to convert FSN in PM because most part of the PM comes from soluble organic fraction, which is not captured by the smokemeter [39]. Since the Dual-Mode Dual-Fuel combustion mode relies on premixed combustion in the major portion of the engine map, this behavior should be also studied. Thus, the objective of the present study is to explore the gaseous emissions and particle size distribution (PSD) of the DMDF concept and compare them with CDC mode.