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Manipulating modern diesel engine particulate emission characteristics through butanol fuel blending and fuel injection strategies for efficient diesel oxidation catalysts

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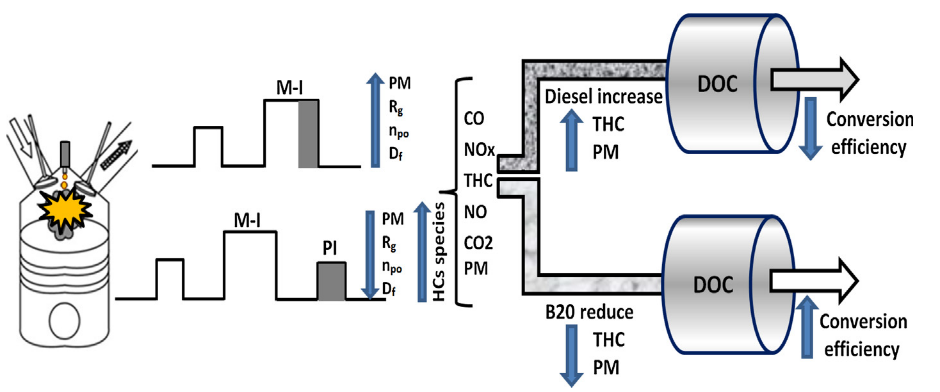
HIGHLIGHTS

- Primary particles emitted from B20 combustion are smaller than diesel fuel particles.
- PM agglomerate emitted from B20 have lower fractal dimension and smaller size than diesel fuel particles.
- The effect of post-injection strategy on PM characteristics has been carried out for B20 and diesel.
- Post-injection strategy with diesel fuel operation is unfavourable for DOC activity.
- PM/soot influence on DOC performance is lower for butanol blend (B20) compare to ULSD.

GRAPHICAL ABSTRACT



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ABSTRACT

Decoupling the dependences between emission reduction technologies and engine fuel economy in order to improve them both simultaneously has been proven a major challenge for the vehicle research communities. Additionally, the lower exhaust gas temperatures associated with the modern and future generation internal combustion engines are challenging the performance of road transport environmental catalysts. Studying how fuel properties and fuel injection strategies affect the combustion characteristics, emissions formation and hence catalysts performance can unveil synergies that can benefit vehicle emissions and fuel economy and as well as guide the design of next generation sustainable fuels. The experimental work presented here was conducted using a modern single-cylinder, common rail fuel injection system diesel engine equipped with a diesel oxidation catalyst (DOC). The impact of the fuel post-injection strategy that is commonly used as part of the aftertreatment system function (i.e. regeneration of diesel particulate filters or activity in hydrocarbon selective reduction of NO_X), combined with butanol-diesel fuel blend (B20) combustion on engine emissions formation, particulate matter characteristics

Abbreviations: aTDC, after top dead centre; B20D80, butanol 20%, and diesel 80%; bTDC, before top dead centre; BSFC, brake specific fuel consumption; CAD, crank angle degree; CI, compression ignition; CO, carbon monoxide; CO_2, carbon dioxide; d_{po}, size of primary particles; DOC, diesel oxidation catalyst; DPF, diesel particulate filter; EGT, exhaust gas temperature; GHSV, gas hourly space velocity; HC, hydrocarbons; IMEP, indicated mean effective pressure; NO, nitric oxide; NO_2, nitrogen dioxide; NO_X, nitrogen oxides; n_{po}, number of primary particles; R_g, radius of gyration; SMPS, scanning mobility particle sizer; PSD, particulate size distribution; PI, post-injection; PM, particulate matter; TEM, transmission electron microscopy; THC, total hydrocarbons; ULSD, ultra low sulfur diesel; M-I, main injection; W/O PI, without post-injection; BTE, brake thermal efficiency.

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(size distribution, morphology and structure) and oxidation catalyst activity were studied. It was found that post-injection produced lower PM concentration and modified the soot morphological parameters by reducing the number of primary particles (n_{po}), the radius of gyration (R_g), and the fractal dimension (D_f). The results were compared with the engine operation on diesel fuel. The increased concentration of HC and CO in the exhaust as a result of the diesel fuel post-injection at the studied exhaust conditions (i.e. T = 300 °C) led in the reduction of the DOC activity due to the increased competition of species for active sites. This effect was improved the combustion of B20 when compared to diesel.

1. Introduction

With the view to improve the air quality, new engine and vehicle systems and technologies are under development in order to reduce pollutants emitted to the atmosphere especially in the very challenging transportation sector [1,2]. In road transport, replacing fossil fuels with biofuels also provide cleaner combustion and consequently improve the efficiency of the catalytic aftertreatment systems and can be considered as a way to help vehicle manufacturers to achieve the emissions legislative limits such as the EURO 6 and CARB (LEV III) [3].

Bioalcohols and other oxygenated fuels have been reported to reduce emissions, when replacing gasoline fuels in spark-ignition (SI) engines. More recently these fuels have been studied as substitute to diesel fuel [4–8] because of their oxygen content that contributes in the reduction of the engine out CO, UHC (unburned hydrocarbons), NO_X (nitrogen oxides) and total PM emissions. It is reported that the hydroxyl group present in alcohols is more efficient in reducing diesel engine PM than other functional groups with the same oxygen content, especially at high engine loads [9–11]. The combustion of diesel-ethanol blends for example has been widely reported to reduce PM emissions [4,12]. However, there are also drawbacks [13,14] such as the ethanol's limited solubility in diesel fuel [15], the very low cetane number and the lower dynamic viscosity, parameters that can impact on the engine's operation and combustion characteristics [4,16,17]. Butanol in diesel has shown more promising characteristics as an alternative fuel to ethanol [4] due to higher cetane number and better solubility in diesel fuel as a consequence of being less polar that other alcohols with shorter chain. Furthermore, it has higher heating value, lower volatility, and less hydrophilic character [18,19].

Modern engine after-treatment systems consist of different components such as the diesel oxidation catalysts (DOC) and diesel particulate filters (DPF) [20]. DOCs have a honeycomb monolith shape with high cell density (large surface area) and suitable loadings of a catalytic material such as platinum and/or palladium that is able to almost eliminate CO, HC and much of the particulate organic fraction [16,20,21]. DOC also oxidise NO to produce NO_2 that can then be utilised in the DPF to passively oxidise soot at low temperatures [16,22,23]. The DOC's activity depends on exhaust gas temperature, residence time of the exhaust gas in the catalyst, level and nature of gaseous and particulate matter exhaust species and inhibitions/synergies between the different species contained in the exhaust gas [23,24]. In the same way, DPF performance is also influenced by size and morphology [fractal dimension (D_f), radius of gyration (R_g) and number of primary particles (n_{po})] of soot particles making understand their control challenging [16,25]. Therefore, the effect of fuel and engine operating parameters such as injection settings (e.g. number of injections, injection timing, injection pressure, injection quantity) needs to be understood in order to improve not only the engine performance (power/torque) characteristics but also the function of the aftertreatment system [26]. Several studies have shown that the post-injection in combination with the DOC is commonly used to increase the exhaust gas temperature in order to aid the DPF regeneration (i.e. active regeneration) [27].

The impact of fuel post-injection on engine out gaseous emissions and PM has also been investigated [28–30]. The temperature increase late in the combustion cycle due to the post-fuel injection, which can enhance soot oxidation, produced during the main combustion event [30–34], but this is reported to be dependent on the engine calibration and operation conditions. Some studies have reported PM increase with post-injection at high engine loads and speeds [28]. In some cases post-injection also contributes in the reduction of engine out NO_X due to the formation of nitrated-hydrocarbons through the reactions of NOx with HC radicals [35,36]. It is reported that CO and THC are reduced with post-injection and sharply increased with later post-injection timing (after 70 CAD ATDC) [27]. Late combustion caused by post-injection increases the level of THC emissions as the late injected fuel is not burnt in the combustion chamber [26,29,37]. In this way, HCs are oxidised in the DOC, increasing considerably the temperature of the exhaust upstream of the DPF and trapping a high proportion of the soot flowing in the exhaust stream [27,38,39]. It is documented that the main-post-injection increases the rate of soot oxidation in the combustion cycle due to the enhancement of the gas mean temperature and air/fuel mixing, which leads to the reduction in number and diameter of primary particles [40,41].

Combined advances in alternative fuels and aftertreatment systems are required in order to fulfil the stringent emission regulations and also help in decoupling mutual dependences between pollutants control and engine fuel economy. Most of the studies on alternative fuels combustion published in the literature are focused on the effect of the fuel on the engine performance and on the engine emissions, including PM characteristics [17] which influences passive and active DPF regeneration [20] as well as DPF trapping efficiency [42,43]. Recent studies have reported work on gaseous emissions interactions [22] and the influence of PM characteristics [16] (size and shape) emitted from the combustion of different fuels on the DOC performance. However, there is still scarce information regarding the effect of alternative fuels (e.g. alcohol blends) on both, PM characteristics and DOC activity with simultaneous use of fuel post-injection, strategy that is required in diesel vehicles for catalyst heat-up in active and DPF regeneration. Therefore, the aim of this research work focuses on the role of the fuel post-injection and diesel-butanol fuel blends combustion on PM characteristics (number, size, morphology) and the impact on the DOC activity. The DOC catalyst activity was assessed under the same temperature, space velocity and pressure conditions with the only comparative parameter being the exhaust gas composition.

2. Experimental setup and materials

A modern single-cylinder, water-cooled, common rail fuel injection system, four-stroke experimental diesel engine was employed in this investigation. The engine used in this study is a single cylinder research engine that was designed by the investigators and