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Interactions between aftertreatment systems architecture and combustion of oxygenated fuels for improved low temperature catalysts activity

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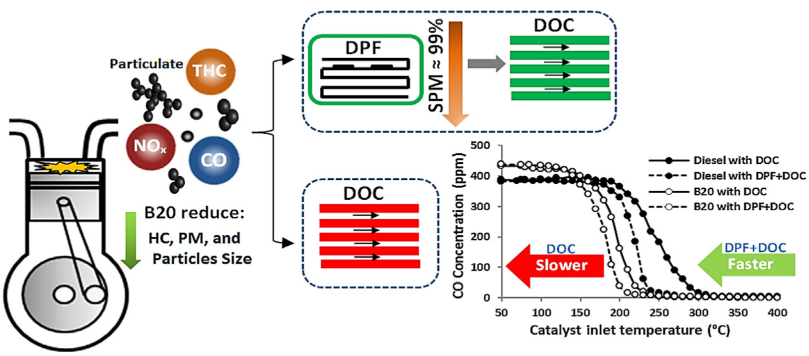
GRAPHICAL ABSTRACT



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ABSTRACT

Diesel engine vehicles, despite their good fuel economy and reduced CO_2, are receiving significant attention and negative publicity in recent years due to their difficulties in achieving the emissions regulations. This has widely been linked to undesirable environmental impact and health effects.

The lower exhaust gas temperatures associated with modern and more efficient hybrid powertrain and diesel engines makes current technology catalytic aftertreatment systems less efficient under range of vehicle operating conditions. This study, demonstrates how changes in the commonly used aftertreatment system architecture and changes in fuel composition in this case through the addition of oxygenated fuels (i.e. butanol) in diesel fuel can provide meaningful low temperature catalyst activity improvements.

The catalyst oxidation kinetics of CO and HC species were improved (reduced the light-off temperature by around 20 °C) when a diesel particulate filter (DPF) was placed upstream of the DOC, while the combination of DPF and combustion of oxygenated fuel in diesel led to up to 80 °C improvement in catalyst activity. The prevention of soot reaching the DOC active sites increases the rate of reactions and the species accessibility to the active sites of the catalyst, and thereby the oxidation of emissions (CO, HC, and NO) can occur at lower catalyst temperatures. The combustion of diesel-butanol blend further improved the DOC low temperature activity. The

Abbreviations: B20, butanol 20%, and diesel 80%; CO, carbon monoxide; CO_2, carbon dioxide; DOC, diesel oxidation catalyst; DPF, diesel particulate filter; GHSV, gas hourly space velocity; HC, hydrocarbons; HHCs, heavy hydrocarbons; HSV, high space velocity; IMEP, indicated mean effective pressure; LSV, low space velocity; NO, nitric oxide; NO_2, nitrogen dioxide; NO_X, nitrogen oxides; PSD, particulate size distribution; PM, particulate matter; SMPS, scanning mobility particle sizer; SPM, solid particulate matter; THC, total hydrocarbons

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major contributors to the improved catalyst light-off, are the reduced level of soot and hydrocarbon emissions as well as the higher reactivity of the hydrocarbons species emitted under butanol blend combustion.

1. Introduction

Modern diesel engine vehicles provide lower fuel consumption, reduced gaseous emissions, and good driving performance. However, nitrogen oxides (NO_x) and particulate matter (PM) emissions emitted form diesel vehicles have been recognized as a major concern for public health and contribute to respiratory cardiovascular diseases [1,2]. The marginal improvements on pollutant emissions from the combustion of fossil fuels when the engine mapping and/or the engine design is modified has led to the extensive research on aftertreatment systems and alternative transportation fuels as ways of meeting the stringent passenger vehicle tailpipe emission regulations [3].

Bioalcohol fuels can improve engine emissions when used in fuel blends with petroleum diesel fuels [3]. The hydroxyl group of the alcohol molecules reduces unburnt total hydrocarbons (THC) and carbon monoxide (CO) as well as soot formation and, in consequence, particulate emissions [4,5]. Alcohol fuels tend to reduce NOx emissions due to their high heat of vaporization and their water content [4,5], while their low cetane number could increase NOx emissions [4]. Therefore, the overall effect will depend on engine technology and engine operation condition. The reported drawbacks with the ethanol-diesel blends such as poor solubility with diesel [6], lower viscosity [7] and lower lubricity [8,9] can be partially resolved with the use of butanol-diesel blends [9]. Longer chain alcohols provide more stable fuel blends at low temperature due to their higher solubility in diesel fuels. Furthermore, butanol has higher heating value, higher cetane number [10] and it is less volatile [11], less hydrophilic and also less polar than other lighter alcohols. However, more studies are needed to assess its energy intesity and green gas house emissions in life cycle analysis, its availablity to replace a realistic share of diesel fuel in the current market and the enhaced biological activity of its exhaust gas as reported in [12].

Aftertreatment systems can include sophisticated technologies such as a diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) [13] or hybrid technologies such as DOC and NOx control catalysts coated on the DPF [14]. DOCs with high cell density (large surface area) and enough loading of catalytic materials such as platinum and/or palladium are able to almost eliminate CO and THC under certain conditions (i.e. [15,16]). DPF is an effective PM trapping and reduction aftertreatment system [17,18]. The introduction of a DOC upstream of the DPF in combination with post-injection can aid DPF active regeneration by increasing exhaust gas temperature with the combustion of post-injected fuel [19] as well as passive regeneration at lower temperature due to the increased NO_2 concentration in the exhaust gas [20,21].

The DOC efficiency in oxidizing CO, THC and NO depends on the residence time of the exhaust gas in the catalyst, the temperature and the level and nature of the exhaust species and inhibitions/synergies between the different species contained in the exhaust gas [22]. Higher space velocity of the exhaust gas, limits the capacity of the gaseous emissions in reaching and interacting with the coated walls of the DOC [23,24]. Post-injection in combination with the DOC is used to increase the exhaust gas temperature in order to aid the DPF regeneration (i.e. active regeneration) [25]. Post injection (timing and quantity) impacts engine output emissions [26–29], sharply increasing CO and THC emissions as the late injected fuel is not burnt in the combustion chamber [28], and thus influencing the aftertreatment performance [17]. Overall THC and CO conversion efficiencies with late post injections are lower than that without post injection due to the increased engine-out CO emissions, which inhibits the THC oxidation inside the DOC as well as the generation of long-chain THC species from post injection with limited diffusivity to reach the DOC active sites to be oxidised [16]. Cleaner fuels can enhance the catalyst activity at lower temperatures because they produce lower emissions concentration during combustion (THC, CO and PM) and reduce the competition of species for catalyst active sites [25,30].

Studies at system level, taking into consideration the combination of fuel properties fuel post-injection strategies, exhaust gas characteristic (i.e. space velocity, emissions concentration, temperature) and aftertreatment systems re-architecture can contribute in fulfilling the forthcoming stringent emission regulations. In this work the light-off activity of a DOC catalyst was studied by manipulating a modern diesel engine exhaust gas composition through the combustion of butanol blending with diesel, fuel post injection strategies, changes in the Gas Hourly Space Velocity (GHSV) and the placement of a DPF upstream the DOC to filter and prevent high molecular weight species such as soot and heavy HC reaching the DOC. The combination of cleaner combustion fuel (i.e. butanol blend) and unconventional aftertreatment architecture (DPF upstream of a DOC) makes more apparent the impact of these carbon species on DOC activity for the case of diesel fuel combustion without upstream DPF.

2. Experimental apparatus, materials and test matrix

2.1. Experimental setup

A single cylinder diesel engine (Table 1) equipped with a high-pressure common-rail fuel injection system that allows the control of pilot injection, main injection, and post-injection (i.e. pressure, injection rate and fuel quantity) has been used in this study. A simplified schematic layout of the experimental set-up is detailed in Fig. 1. The engine exhaust is linked to a bespoke catalyst test rig that allows catalyst activity and characterisation studies. The mini reactor was positioned inside a furnace and a sample of the engine exhaust gas was directed to the reactor. The facility allows parameters such as temperature, pressure and space velocity to be selected according to the study requirements. The combined arrangement of DPF and DOC aftertreatment systems is also shown (see Fig. 1).

An electric dynamometer with motor and a load cell was used to control the engine load. A digital shaft encoder (producing 360 pulses per revolution) was used to measure the crankshaft position and the pressure transducer mounted at the cylinder head and connected via an AVL FlexiFEM 2P2 charge amplifier was used to measure in-cylinder pressure. To monitor intake air flow rate, pressure, and temperature (oil, air, inlet manifold and exhaust), standard engine test rig instrumentation was used. A bespoke LabVIEW based code was used to perform data acquisition and combustion analysis. Furthermore, the

Table 1
Research engine specifications.

Engine parameters	Specifications
Engine type	Diesel 1- cylinder
Stroke type	Four-Stroke
Number of cylinders	1
Cylinder bore x stroke (mm)	84 × 90
Connecting rod length (mm)	160
Compression ratio	16.1
Displacement (cm^3)	499
Injection system	Common rail
Fuel pressure range (bar)	500–1500
Pre, main and post injection timing	15, 3 and -60 deg bTDC
Number of injections	3 injection events