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Diesel engine emissions with oxygenated fuels: A comparative study into cold-start and hot-start operation

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ABSTRACT

As biofuels are increasingly represented in the fuel market, the use of these oxygenated fuels should be evaluated under various engine operating conditions, such as cold-start. However, to-date quantification has been mostly done under hot-start engine operation. By using a custom test designed for this study, a comparative investigation was performed on exhaust emissions during cold- and hot-start with diesel and three oxygenated fuels based on waste cooking biodiesel and triacetin. This study used a six-cylinder, turbocharged, after-cooled diesel engine with a common rail injection system. The results during cold-start with diesel showed lower NOx (up to 15.4%), PN (up to 48%), PM_1 (up to 44%) and $PM_{2.5}$ (up to 63%). However, the oxygenated fuels during cold-start showed a significant increase in NOx (up to 94%), PN (up to 27 times), PM_1 (up to 7.3 times) and $PM_{2.5}$ (up to 5 times) relative to hot-start. The use of oxygenated fuels instead of diesel during hot-start decreased the PN, $PM_{2.5}$ and PM_1 (up to 91%) while, during cold-start, it only decreased PM_1 and $PM_{2.5}$ at some engine operating modes and increased PN significantly up to 17 times. In both cold- and hot-start, the use of oxygenated fuels resulted in an increase in NOx emission. For cold-start this was up to 125%, for hot-start it was up to 13.9%. In comparison with hot-start, the use of oxygenated fuels during cold-start increased nucleation mode particles significantly, which are harmful. This should be taken into consideration, since cold-start operation is an inevitable part of the daily driving schedule for a significantly high portion of vehicles, especially in cities.

1. Introduction

This study investigates the influence of oxygenated fuels on exhaust emissions during cold-start, with a comparison to hot-start. During cold-start, the engine temperature is sub-optimal owing to lower temperatures of three interrelated thermal masses: the main engine block, the engine coolant and the lubricant oil (Roberts et al., 2014). Driving when the engine temperature is lower than its optimal value influences engine performance and emissions (Roberts et al., 2014; Roy et al., 2016). For example, the low temperature of the engine cylinder wall was reported to be a reason for higher emissions and fuel consumption (Roberts et al., 2014). A study by Cao (2007) demonstrated that a cold engine block, which can cause incomplete combustion, can significantly affect emissions. Additionally, the higher viscosity of the engine lubricant due to its low temperature increased friction losses and decreased thermal efficiency (Roberts et al., 2014). The friction losses during cold-start increased up to 2.5 times, compared to when the engine is warmed up (Will and Boretti, 2011). To overcome high friction losses and to maintain brake power output, more fuel must be injected into the cylinder during cold-start, regardless of the ambient temperature (Will and Boretti, 2011; Khair and Jääskeläinen, 2013). A study showed a 13.5% increase in fuel consumption during cold-start compared to hot-start (Samhaber et al., 2001).

Emissions during cold-start are a significant proportion of an engine's total emissions (Sakunthalai et al., 2014; Reiter and Kockelman, 2016). Nam (2008) estimated that particulate matter (PM) emissions during the cold-start phase of the LA92 Unified

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Driving Cycle, Phase 1, can consist of up to 30% of total PM emission from that cycle. This is despite Phase 1 only being a 12% and 21% proportion of the entire cycle distance and duration, respectively. They also showed that PM emission from Phase 1 is 7.5 times higher than phase 3, which is a hot-start phase with the same driving schedule as Phase 1. Another report showed that PM and hydrocarbons (HC) were several times higher during the first three minutes of cold-start operation compared to the time the engine was warmed up; more than 40% of total emissions were related to those first three minutes (Bielaczyc et al., 2001). Lee et al. (2012) used the FTP test and demonstrated that nitrogen oxides (NOx), CO and HC emitted from a cold engine, in comparison to a warmed up engine, can be up to two, three and four times higher, respectively.

There are different definitions for cold-start in the literature. Reiter and Kockelman (2016) reviewed some of them. Based on the literature, this study considers cold-start to be an engine starting after an overnight soak (engine-off time) and persisting until the engine coolant temperature reaches 70 °C, inline with EU Directive 2012/46/EU. This investigation also studies a condition in which the engine coolant temperature is above 70 °C but the engine lubricant temperature is still sub-optimal.

A significant proportion of daily driving starts and finishes while the engine temperature is still below its regular operating level (Reiter and Kockelman, 2016). A study of the driving patterns of 55 French cars, which included 1000 trips (71,000 km representing 1260 h), under real conditions showed that one third of the journeys were completed before the engine coolant and lubricant exceeded 70 °C (André, 1991). It should be noted, however, that the cold-start time and distance depend on emission species (André and Joumard, 2005; Reiter and Kockelman, 2016). André and Joumard (2005) studied and modeled excess emission during cold-start based on a survey of 39 European laboratories. The data they used were obtained from 1766 vehicles and 35,941 measurements. They estimated an average distance of 5.2 km for the cold-start distance, the average distance at which emissions (CO, CO_2, HC and NOx) stabilised, at an ambient temperature of 20 °C. It should be mentioned that most of these reports are based on conventional petro-diesel.

Over the last few decades, biofuel has displaced some conventional fuels, but petro-diesel is still the most common type of diesel fuel. Using biofuel instead of fossil fuels is relevant due to the adverse health effects, environmental degradation and the impact on global warming caused by fossil fuels. These negative points contributed the European Union's directive to increase the use of renewable biofuels to 10% by 2020 in order to offset fossil fuel usage (EU Directive 2009/28/EC). The commitment to reduce fossil fuel use was reinforced when 195 countries agreed to limit global warming in the Paris agreement (December 2015, Paris climate conference (COP21)).

The use of biodiesel instead of diesel has some advantages in reducing air pollution, such as lower PM (Rahman et al., 2014a,b,c), particle number (PN) (Nabi et al., 2016), CO (Ahmed et al., 2014; Ruhul et al., 2016), HC (Rahman et al., 2014a,b,c; Sanjid et al., 2014; Sanjid et al., 2016) and CO_2 (Zare et al., 2016) emissions; however, they can potentially lead to more toxic emissions that should also be considered (Stevanovic et al., 2013; Hedayat et al., 2016). Among the different types of biofuel, waste cooking biodiesel has the potential to be used as a fuel due to advantages such as global availability, close properties to diesel and low price (Kulkarni and Dalai, 2006). Doroda et al. (2003) studied the effect of waste olive oil, as a fuel, on engine emissions. They reported that CO and CO_2 emissions decreased by up to 58.9% and 8.6%, respectively. While, NO_2 emission showed an increasing trend. A recent study from our research group demonstrated that using waste cooking biodiesel, instead of diesel, can decrease PM, PN, CO (at higher loads), HC, and CO_2 emissions; however NOx emissions showed an increasing trend (Zare et al., 2016).

Different fuel properties have been used to interpret the changes in exhaust emissions, such as fuel oxygen content (Rahman et al., 2014a,b,c). The presence of long-chain alkyl esters, which have two oxygen atoms per molecule, is an influential factor that distinguishes biofuels from conventional fossil fuels. However, the oxygen content in biofuels is related to the fatty acid profile such as carbon chain length and unsaturation level (Pham et al., 2014). Since the presence of oxygen in fuel can reduce emissions, a low volume of a highly-oxygenated fuel additive can significantly reduce emissions.

Triacetin [$C_9H_{14}O_6$]—a triester of glycerol acetic acid—could be introduced as an additive to biodiesel (Casas et al., 2010). Since glycerol is a byproduct of the biodiesel transesterification process, its production will increase proportionally with an increase in the production of biodiesel. Consequently, this can reduce the price of this feedstock. However, there are some limitations to using glycerol directly as a fuel due to its physical and chemical properties (Gupta and Kumar 2012). The solution could be triacetin, a glycerol-derived product, which is produced by the acetylation process of glycerol and acetic acid (Lapuerta et al., 2015). Mixing this highly-oxygenated additive with biodiesel increases fuel oxygen content, viscosity and the density of the blend, while the heating value and cetane number of the blend decreased (Casas et al., 2010). There is limited published research on triacetin as a fuel in engines (Nabi et al., 2015; Zare et al., 2015; Hedayat et al., 2016; Nabi et al., 2016; Zare et al., 2016; Zare et al., 2017a,b). A recent study by Zare et al. (2016) showed that, by increasing the share of triacetin in the blend, the PM and PN emissions decrease while NOx and HC emissions increase.

Due to the increasing share of biofuels in the fuel market, the use of these oxygenated fuels should be evaluated under different engine operating conditions such as cold- and hot-start. This quantification is essential to evaluate the possible use of these alternative fuels in the market. As already discussed, cold-start engine operation is an inevitable part of the daily driving schedule for a considerably high portion of vehicles in cities (André, 1991). However, most studies have only focused on hot-start engine operation.

This paper investigates the influence of oxygenated fuels on exhaust emissions during cold-start, with a comparison to hot-start, using four fuels with oxygen contents ranging from 0% to 13.57%, based on diesel, waste cooking biodiesel and triacetin as an additive.

A thorough search in the literature could not find any comparative study into exhaust emissions during cold-start and hot-start using triacetin as a fuel additive with waste cooking biodiesel. However, some results during hot-start have been investigated in a recent study by our research group (Zare et al., 2016). More detailed information about this study is discussed in Section 3 in a critical comparison of results.

2. Experimental facilities

2.1. Engine specifications and test setup

In order to achieve the stricter emission standards of EURO IV-VI, engines are typically equipped with emission-control devices. As such the emissions can also be dependent on the type of after-treatment devices used. To avoid this, and to gain better insight into the actual engine dependent emissions, it was decided to use a EURO III engine. Here, different after-treatment systems can be mentioned. For example, Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR), which could be used to abate the