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The effect of triacetin as a fuel additive to waste cooking biodiesel on engine performance and exhaust emissions

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HIGHLIGHTS

- Oxygen ratio was used instead of the equivalence ratio.
- Oxygen ratio decreases with engine load, but increases with engine speed.
- IMEP, BMEP, friction power, CO_2, HC, PM and PN decreased with oxygenated fuels.
- BSFC, BTE and NOx increased with oxygenated fuels.
- Accumulation mode count median diameter decreased with oxygenated fuels.

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ABSTRACT

This study investigates the effect of oxygenated fuels on engine performance and exhaust emission under a custom cycle using a fully instrumented 6-cylinder turbocharged diesel engine with a common rail injection system. A range of oxygenated fuels based on waste cooking biodiesel with triacetin as an oxygenated additive were studied. The oxygen ratio was used instead of the equivalence ratio, or air to fuel ratio, to better explain the phenomena observed during combustion. It was found that the increased oxygen ratio was associated with an increase in the friction mean effective pressure, brake specific fuel consumption, CO, HC and PN. On the other hand, mechanical efficiency, brake thermal efficiency, CO_2, NOx and PM decreased with oxygen ratio. Increasing the oxygen content of the fuel was associated with a decrease in indicated power, brake power, indicated mean effective pressure, brake mean effective pressure, friction power, blow-by, CO_2, CO (at higher loads), HC, PM and PN. On the other hand, the brake specific fuel consumption, brake thermal efficiency and NOx increased by using the oxygenated fuels. Also, by increasing the oxygen content, the accumulation mode count median diameter moved toward the smaller particle sizes. In addition to the oxygen content of fuel, the other physical and chemical properties of the fuels were used to interpret the behavior of the engine.

1. Introduction

High fuel prices, global warming, environmental degradation and adverse health effects of fossil fuels have been a topic for a significant amount of recent engine research in the last decade [1]. The European Union issued a directive to offset fossil fuel usage with renewable biofuels by 10% by 2020 (EU Directive 2009/28/EC). Fuel specific solutions to this issue range from finding new sources of fuel or adding additives to fossil fuels.

Recently several types of biofuel have been introduced by researchers and industry. Waste cooking oil has received attention due to its low price, close properties to diesel and global availability [2]. Disposal issues including dumping waste cooking oil into waterways could be another reason to use it as a fuel [3]. The current literature shows some advantages and disadvantages for the use of waste cooking biodiesel [4]. A study reported that using waste olive oil decreased CO up to 58.9% and CO_2 by up to 8.6%; however, NO_2 and BSFC (brake specific fuel consumption) increased [5]. Similarly, another study also reported an increase in NOx, with a subsequent decrease in PM [4].

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The oxygen-bond in biofuels is a significant factor that makes them different from conventional petro-diesel. Most biofuels, such as those from animal fats, vegetable oils and waste cooking oil, contain long-chain alkyl esters which have two oxygen atoms per molecule. However, the fuel oxygen content is derived from the fatty acid ester profile such as unsaturation level and carbon chain length [6].

In terms of emission reduction, the oxygen content of the fuel has been reported to be a major factor compared to the other properties [7–9]. In this regard, a low volume of fuel additives with high oxygen content could play an import role boosting the emission reduction.

As a highly oxygenated additive to fuel, triacetin [$C_9H_{14}O_6$] (a triester of glycerol acetic acid) could be used in combustion process [10]. Glycerol is a byproduct of the biodiesel transesterification process and is therefore readily available, especially given that the production of waste glycerol will increase proportionally by increasing the production of biofuels. Utilisation of this cost-effective feedstock as a fuel is possible, however, the physical and chemical properties of direct glycerol have limited its usage for this purpose [11]. Accordingly, triacetin as the product of acetylation process of glycerol and acetic acid could be used instead.

A thorough search could not identify any publication in the literature investigating the effect of triacetin as a fuel additive with waste cooking biodiesel. However, a recent study showed that blending triacetin with biofuels increased the oxygen content, density and kinematic viscosity; however the cetane number and heating value of the blend reduced [10].

This paper intends to study engine performance and exhaust emission using a range of fuels with 0–14.23% oxygen content, based on waste cooking biodiesel as the primary fuel and triacetin as a highly oxygenated additive.

2. Experimental facilities

2.1. Engine specification

In this experimental study a 6-cylinder turbocharged after-cooled diesel engine with a common rail injection system was used. An electronically controlled water brake dynamometer was coupled with this engine to control the steady-state and transient load on the engine. Regarding the indicated parameters, a piezoelectric transducer (Kistler 6053CC60) with a simultaneous analog-to-digital converter (Data Translation DT9832) were utilised to collect the in-cylinder data, crank angle and engine speed data were collected by a crank angle encoder set (Kistler type 2614). In addition, a blow-by sensor was utilised to measure the exhaust flow from the engine crankcase. For more specific information about the engine and experimental facilities readers can refer to Ref. [12]. Table 1 shows the test engine specification.

Table 1
Test engine specification.

Model	**Cummins ISBe220 31**
Cylinders	6 in-line
Capacity	5.9 L
Bore × stroke	102 × 120 (mm)
Maximum power	162 kW @ 2000 rpm
Maximum torque	820 Nm @ 1500 rpm
Compression ratio	17.3:1
Aspiration	Turbocharged
Fuel injection	High pressure common rail
Dynamometer type	Electronically controlled water brake dynamometer
Emission standard	Euro III

2.2. Exhaust sampling and test setup

Exhaust emissions were sampled from the exhaust manifold via a 0.5 m long stainless steel tube. Apart from a fraction which was sent to the gas analysers via a copper tube fitted with a HEPA filter, the rest passed through the dilution tunnel and then to the particle measuring systems. Fig. 1 shows the schematic diagram of the test setup.

2.3. Fuel selection

Table 1 shows the set of fuels used in this study. Except neat diesel (D100) and D60B35T5, the blends were made based on the waste cooking biodiesel (B) as the primary fuel and triacetin (T) as an additive. The first row of this table shows the 6 different fuels used in this study classified by the portion of each fuel in the final fuel. For example, T8B92 stands for 8% (by volume) of triacetin added to 92% (by volume) of waste cooking biodiesel. The miscibility and stability of blends were tested at the room temperature for 96 h and no phase separation was observed.

The oxygen content of the selected fuels ranged from 0 to 14.23%. Increasing the oxygen content of the fuel decreases the lower heating value (LHV), which in turn negatively affects the engine power. In addition, the kinematic viscosity of the fuel, which is related to the degree of unsaturation, increases with the fuel oxygen. This can adversely affect the atomisation of the fuel spray and evaporation characteristics of the fuel during combustion [1].

The values for the blends listed in Table 2 are estimated based on pure substance compositions. For more information about triacetin and waste cooking biodiesel, the reader can refer to Ref. [10] and a recent publication from our research group [13].

2.4. Design of experiment

Driving cycles which show the driving pattern are not only used to model the exhaust emission, but also to evaluate fuel consumption and engine performance. Driving cycles are classified based on the driving pattern. The first category which is composed of different quasi steady-state modes of speed and load is called “modal” or “polygonal”, and the second one, real world driving cycles are based on actual driving data [14].

In the literature, many investigations used real world driving cycles such as US Federal Test Procedure (FTP) transient cycle [1]. These driving cycles contain a very large amount of transient fluctuations with rapid changes which limit the fundamental investigations on transient response. Hence a modal controllable driving cycle with a gentle mode change may help a more fundamental investigation in both transient response and steady-state response [15]. To date, the number of investigations using controllable transient conditions are limited [1,15,16].

It is preferable to use existing modal driving cycle from the literature, however no suitable example could be found to achieve the research goals of the investigation. Hence, a custom cycle based on modal driving cycle schedule with some controllable transient modes was designed to evaluate the engine performance and exhaust emission during steady-state and transient discrete modes of operation. Since the engine used in this study has a Euro III emission certification, to design this custom cycle, speed and torque were selected from European Stationary Cycle (ESC) driving cycle pattern, which was a legislated test cycle for heavy-duty engines in the Euro III legislation.

Unlike the ESC, which has a sharp change between steady-state modes, different controllable transient ramps were added between the steady-state modes instead of sharp changes. The concept was based on the Supplemental Emissions Test (SET) introduced in the