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# Influence of engine load and speed on regulated and unregulated emissions of a diesel engine fueled with diesel fuel blended with waste cooking oil biodiesel

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ABSTRACT

This study is focused on investigating the regulated and unregulated emissions of a 4-cylinder natural-aspirated direct-injection diesel engine fueled with neat diesel fuel, B10 (diesel containing 10 vol.% of biodiesel), B20, B30 and neat biodiesel (B100). Experiments were conducted on the Japanese 13-mode test cycle for the diesel engine so that the influence of engine load and engine speed on the regulated and unregulated emissions can be identified. The 13-mode weighted results show that with an increase of biodiesel in the blended fuel, there are reductions of HC, CO and particulate mass concentrations but an increase in $NO_x$. For the unregulated emissions, formaldehyde and acetaldehyde emissions increase with increasing biodiesel content. The same trend can be observed for 1,3-butadiene, propene and ethene. For the aromatics emissions, biodiesel addition leads to an increase in benzene emission but reductions in toluene and xylene emissions. The results also show that all the emissions are affected by the engine operating modes, especially the engine load.

## 1. Introduction

The increasing energy demand and environmental deterioration are two major factors which drive for the search of alternative fuels for replacing the conventional petroleum fuels for motor vehicles. Among all the alternative fuels, biodiesel is one of the most widely investigated as a replacement for diesel fuel due to its renewability, potential of reducing greenhouse gas emissions, and inhibition of soot formation [1–3]. In addition, there is no need to modify the diesel engine when biodiesel is applied in either the neat form or in the blended form [4]. Therefore, extensive studies have been conducted on diesel engines fueled with biodiesel or biodiesel/diesel blends [5–8]. In general the use of biodiesel will lead to increase in fuel consumption, reductions in HC, CO, smoke and particulate emissions and a slight increase in $NO_x$ emission. Furthermore, several theoretical and computer modeling studies provided insights into the biodiesel combustion and emission characteristics [9–11]. Mohamed Ismail et al. [10] conducted a computational fluid dynamics (CFD) simulation on biodiesel combustion, using a reduced methyl butanoate mechanism combined with a n-heptane mechanism. The simulated results show that the proposed mechanisms give reliable predictions of in-cylinder combustion and emission processes.

A number of investigations on the influence of biodiesel on the unregulated emissions of a diesel engine have been carried out. Sharp et al. [12] conducted investigations on three diesel engines using diesel fuel, B20 and B100. The biodiesel used was soybean oil biodiesel. They found reduced emissions of speciated vapor phase hydrocarbons in the $C_1$ to $C_{12}$ range and reduction in aldehydes. USEPA [13] reported reductions in acetaldehyde, formaldehyde and xylene, but inconsistent results in benzene, 1-3-butadinene and toluene. McGill et al. [14] conducted tests on different engines and test cycles, using rapeseed biodiesel, soy bean biodiesel and used vegetable oil biodiesel. They concluded that the unregulated emissions of interest – aldehydes and 1,3-butadiene – did not seem to have much dependence on the fuel. Correa and Arbilla [15] investigated the influence of castor oil biodiesel on the carbonyl emissions of a six-cylinder heavy-duty diesel engine using B2, B5, B10 and B20. Experiments were conducted at three engine speeds but the engine load was not specified. They found increase in both formaldehyde and acetaldehyde emissions. Peng et al. [16] also investigated the aldehyde emissions of a 4-cylinder diesel engine under the US transient cycle protocol,

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using diesel fuel blended with 20% waste cooking oil biodiesel. The results show lower formaldehyde emission but higher acetaldehyde emission. Di et al. [17] conducted investigations on a 4-cylinder diesel engine using waste cooking oil biodiesel, with B20, B40, B60, B80 and B100 at an engine speed of 1800 rpm on five engine loads. They found decrease of formaldehyde, increase in acetaldehyde, reduction in 1,3-butadiene, increase in benzene and reductions in toluene and xylene. Cheung et al. [18] investigated on a 4-cylinder diesel engine using neat waste cooking oil biodiesel at an engine speed of 1800 rpm on five engine loads. They found increase of formaldehyde and acetaldehyde and reductions in 1,3-butadiene, benzene, toluene and xylene.

Besides investigations on the carbonyls and the aromatics, experimental work has also been conducted on other species. Karavalakis et al. [19] investigated 16 PAHs, 4 nitro-PAHs, 6 oxy-PAHs and other unregulated emissions of a 2.2 litre common-rail diesel engine with an oxidation catalyst on a chassis dynamometer over the New European Driving Cycle and the Artemis driving cycle. Lin et al. [20] used waste cooking oil biodiesel to investigate the trace species in the emissions of a diesel engine while Grigoratos et al. [21] investigated the effects of rapeseed biodiesel on the inorganic ions.

Lapuerta et al. [6] commented that the information given in the literature about the effects of biodiesel on the unregulated emissions is scarce. There is no conclusive trend regarding the emissions of oxygenated compounds, including the aldehydes. Xue et al. [4] reported that most research showed that the aromatic and polyaromatic emissions for biodiesel reduced with regard to diesel while for carbonyl emissions, there are discordant results despite it is widely accepted that biodiesel increases these emissions because of the higher oxygen content.

The above review shows that there is a need to further investigate on the unregulated emissions of a diesel engine when using waste cooking oil biodiesel and diesel/biodiesel blended fuel under different engine loads and engine speeds. To fill in this knowledge gap, in this study, the unregulated emissions of a diesel engine are investigated under the Japanese 13-mode test cycle for diesel engine which covers three engine speeds and different engine loads at each engine speed, using biodiesel derived from waste cooking oil, pure diesel and three diesel/biodiesel blends. The unregulated emissions investigated include formaldehyde, acetaldehyde, 1,3-butadiene, ethene, propene, benzene, toluene and xylene which are classified as air toxics by USEPA and the maximum incremental reactivity (MIR) of some of them are very high. For example, the MIR of formaldehyde, acetaldehyde, 1,3-butadiene, ethene, propene and xylene are higher than 6 [22], indicating their significant influence to ozone formation.

## 2. Experimental

The experiments were carried out on a 4-cyclinder natural-aspirated direct-injection diesel engine fueled with different mixed concentrations of biodiesel and diesel fuel, including pure diesel fuel, B10 (diesel containing 10 vol.% of biodiesel), B20, B30 and pure biodiesel. The blended fuel is limited to B30 because higher biodiesel/diesel blends are not in common use. Specifications of the engine are listed in Table 1 while the experimental setup is shown in Fig. 1. The engine was coupled with an eddy-current dynamometer and a control system (Ono Sokki system) was used to adjust the engine speed and torque. The diesel fuel used contains less than 10-ppm-wt of sulfur while the biodiesel used in present study was manufactured from waste cooking oil by Dynamic Progress Ltd., complying with EN14214. The composition of the biodiesel was analyzed and the results are shown in Table 2. The FAMEs were measured using the Agilent GC 7890A with FID and Supelco SP-2560 column, with each FAME calibrated against C11 signal which was complied with the gas chromatographic analysis as stated in the AOAC Official Method 996.06 [23]. The biodiesel contains mainly Methyl palmitate (11.46%), Methyl oleate (35.22%) and Methyl linoleate (39.73%), which is very close to the major FAMEs in the waste cooking oil biodiesel used in Lapuerta et al. [7] and in Armas et al. [24]. The major physical–chemical properties of the tested fuels are listed in Table 3 which are the same as the fuels used in Zhu et al. [25] and Man et al. [26].

**Table 1**
Engine specifications.

| Model | Isuzu 4HF1 |
|---|---|
| Type | In-line 4-cylinder |
| Maximum power | 88 kW/3200 rev/min |
| Maximum torque | 285 N m/1800 rev/min |
| Bore × stroke | 112 mm × 110 mm |
| Displacement | 4334/cc |
| Compression ratio | 19.0:1 |
| Fuel injecting timing (BTDC) | 8° |
| Injection pump type | Bosch in-line type |
| Injection nozzle | 5 × 0.3 mm × 130° (with 5 orifices) |

The regulated gaseous emissions analyzed include unburned hydrocarbon (HC), nitrogen oxides ($NO_x$) and carbon monoxide (CO), using the following standard equipment: a heated flame ionization detector (HFID, CAI Inc.) for HC; a heated chemiluminescence analyzer (HCLA, CAI Inc.) for $NO_x$; and non-dispersive infra-red analyzers (NDIR, CAI Inc.) for CO and $CO_2$. To ensure the accuracy of the experimental data, each gas analyzer was calibrated with the corresponding standard gas and the zero gas in each experiment.

The unregulated emissions, including formaldehyde, acetaldehyde, 1,3-butadiene, propene, ethene and BTX, were measured with a V&F multi-components gas analyzer (V&F Airsense Net) which is an Ion Molecule Reaction (IMR) mass spectrometer capable of detecting concentrations at ppb level. According to the equipment supplier, the lower detection limit is 1 ppb for benzene in exhaust gas. The principle of operation can be found in Refs. [27–29]. Standard gases were also used to calibrate all the measured unregulated emissions before conducting each test.

The particulate mass concentration was measured with a tapered element oscillating microbalance (R&P TEOM 1105). A Dekati mini-diluter was used to dilute the exhaust gas before passing it to the TEOM. The dilution ratio was determined from the measured $CO_2$ concentrations of background air, undiluted exhaust gas and diluted exhaust gas and it varied from 5.5 to 8.5 depending on the actual engine operating conditions. The fuel consumption was measured with an electronic balance with sensitivity of 0.1 g (Shimadzu Balance, Model BX-32KH).

The Japanese 13-mode test cycle for diesel engine was adopted to evaluate the effect of the biodiesel on the regulated and unregulated emissions. The operating conditions of each mode are listed in Table 4. At each operating condition, after the engine has attained the steady state operating conditions, as indicated by the stabilized exhaust gas temperature, cooling water temperature and lubricating oil temperature, the experimental data were recorded for a period of five minutes and the average results over the 5-min period are presented in this paper. Furthermore, in order to assess the repeatability and experimental uncertainty of the experimental results, each experiment was repeated twice. The experimental results were found to agree with each other within the 95% confidence level. The experimental uncertainty (at 95% confidence level) and standard errors in the measurements as determined based on the method of Kline and McClintock [30] are shown in Table 5.