Energy 90 (2015) 266–273

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Comparison of carbonyl compound emissions from a diesel engine generator fueled with blends of *n*-butanol, biodiesel and diesel

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ARTICLE INFO

Article history:
Received 26 July 2014
Received in revised form
4 May 2015
Accepted 21 June 2015
Available online 14 August 2015

Keywords:
Alternative energy
Butanol
Carbonyl compounds
Diesel engine

ABSTRACT

Biodiesel can be produced from animal fats or vegetable oils with methanol or ethanol as the catalyst via transesterification. Although blends of biodiesel/diesel/alcohol are well known in emission reduction, butanol has been recently found to have economic and sustainable potentials as a substitute for ethanol in diesel blends. This study investigates the emissions of CBCs (carbonyl compounds) and regulated traditional pollutants that are produced from diesel engine combustion in idle mode. Diesel/biodiesel mixtures and diesel/biodiesel/butanol blends are compared with premium diesel fuels in terms of their emissions. Experimental results indicate that formaldehyde and acetaldehyde are the primary and secondary carbonyls in the exhaust, which account for 76.0–57.2 vol.% of total CBC concentrations for all test fuels (including diesel). We demonstrate that using B10W30 and B10W40 as alternative fuels significantly decreases FOR (formaldehyde) concentrations by 16.6 and 20.1 vol.%, respectively. It is also found out that using B10W40 instead of D100 is able to reduce particulate matter (PM) and nitrogen oxide (NO_X) by 31.9 and 57.1 vol.%, respectively. Moreover, adding 10 vol.% butanol in biodiesel blends results in a decrease of FOR (formaldehyde) and ACE (acetaldehyde) formation. A decrease in FOR and ACE concentrations is proportional to the butanol–biodiesel content in the blends.

1. Introduction

An increasing depletion of petroleum resources from environment and the worsening pollution problems have led to awareness of petroleum alternatives. It is by now well known that the EU has set a target of replacing 10% of conventional fuels with biofuels by 2020 [1]. As renewable, biodegradable, and nontoxic fuel research has continued to the present, biodiesel has attracted considerable amount of attention over the past decade. Among biodiesel feedstock, the biodiesel made from waste cooking oil can be used to effectively reduce the raw material cost as well as solve the problem of waste oil disposal [2,3].

Diesel–powered engines are used worldwide in heavy–duty buses, trucks, construction machines, marine, and generators because of their advantages in output power and fuel efficiency. The purposes of the diesel engines can be dived into on–road or non–road (off–road). The relevant studies of non–road diesel engine have not been widely investigated yet. In many suburban and rural districts, the supply of portable diesel-engine generators has not caught up with its rising demands for decentralized electrification applications [4]. Furthermore, off-road diesel engines are less explored in comparison to on-road diesel engines. There is thus a need to analyze carefully the use of oxygenated fuels in off-road diesel engines.

Some studies indicated that biodiesel from waste cooking oil can reduce emissions of PM (particulate matter), HC (hydrocarbon), CO (carbon monoxide), and PAHs (polycyclic aromatic hydrocarbons) from engines [5,6]. However, the previous engine studies showed increases of NO_X (nitrogen oxide) emissions from biodiesel combustion [7]. Three primary techniques have been proposed in order

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http://dx.doi.org/10.1016/j.energy.2015.06.070
0360-5442/

Nomenclature

BSFC	brake specific fuel consumption (g kW hr^{-1})
BSEC	brake specific energy consumption (KJ kW hr^{-1})
CO	carbon monoxide (% volume)
NO_X	nitrogen oxide (ppm volume)
PM	particulate matter (μg Nm^{-3})
CBCs	carbonyl compounds
FOR	formaldehyde
ACE	acetaldehyde
ACR	acrolein
ATN	acetone
PRO	propionaldehyde
CRO	crotonaldehyde
BUT	butyraldehyde
MEK	methyl ethyl ketone
BEN	benzaldehyde
ISO−VAL	isovaleraldehyde
VAL	valeraldehyde
o−TOL	o−tolualdehyde
m−TOL	m−tolualdehyde
p−TOL	p−tolualdehyde
HEX	hexaldehyde

to lower NO_x formation from combustion of biodiesel: (a) using low-temperature combustion, (b) employing reformulated biodiesel and selective catalytic reduction, and (c) utilizing exhaust gas recirculation [8–10]. Recently, using bio-alcohol as an additive in biodiesel has shown a great potential solution to reduce NO_X emissions from biodiesel due to the increases of vaporization heat and oxygen contents in the biodiesel blends. Among the alcohols, butanol can be particularly advantageous fuel components due to its greater heating value, higher cetane number and miscibility, and lower vapor pressures. Butanol is produced by the fermentation of biomass, resulting in lower cost of production and less corrosive. Furthermore, the carbon chain of butanol is twice that of methanol and ethanol, which implies that butanol has higher heating values and efficiency in combustion [11]. Previously, experimental results showed that the addition of butanol to diesel fuel is able to considerably lower soot formation and slightly reduce CO and NOx emissions [12,13]. However, both HC emissions and BSFC (brake specific fuel consumption) are increased [12,13].

Carbonyls are among the major species of organic compounds involved in photochemical air pollution since aldehydes and ketones play an important role as products of photo−oxidation for gas−phase hydrocarbons in sunlight. CBCs (Carbonyl compounds) are formed inside engine combustion or found in diesel fuel. Emissions produced from a diesel engine or vehicle like FOR (formaldehyde), ACE (acetaldehyde), and ATN (acetone) are toxic contaminants, mutagens, and carcinogens [14,15]. In addition, FOR is classified as group 1 (human carcinogen) by the IARC (International Agency for Research on Cancer) for its carcinogenicity (IARC, 2006) and ACE is classified as a suspected carcinogen [15].

CBC emissions from diesel engines have recently drawn attention. Different research groups investigated CBC emissions from diesel engines fueled with Castor oil biodiesel (2–20 vol%), residual oil biodiesel (2–100 vol%), cooking oil biodiesel (20 vol%), and BE−diesel (5 vol% ethanol, 20 vol% soy−biodiesel, 75 vol% base diesel fuel, and commercial Chinese in−use diesel fuel) [16–19]. It was found that FOR and ACE can be increased by 2.6–35.5% and 1.4–15.8%, respectively, using different additives including B2 (2 vol % Castor oil biodiesel), B5, B10 and B20. Several studies showed that BE−diesel [16] and waste cooking oil biodiesel (20 vol%; [20]) are able to reduce FOR emissions by about 20–25% and 23%. However, the authors found that ACE emissions are increased by 17% in waste cooking oil biodiesel. Recently, biodiesels associated with increases in contaminants (particularly FOR and ACR/ATN [1]) have been those derived from rapeseed oil (10 vol%) and palm oil (10 vol%). From the literature reviewed above, it is seen that identifying an alternative fuel to reduce CBC emissions, especially FOR and ACE, is important.

Previous studies have reported carbonyl emissions from the use of biodiesel mixed with butanol. Ballesteros et al. [21] used the new European Driving Cycle and a pure diesel fuel as a reference to contrast with two biodiesel blends in experiments: (1) 10% v/v of bioethanol and (2) 16% v/v of butanol. The results showed that carbonyl emissions from the tested blends were higher than those for diesel. Nevertheless, the authors observed that the blends of bioethanol compared with pure diesel show higher concentrations for some emission products. Sukjit et al. [22] suggested that there is a dramatic reduction in CO and PM emissions and a small increase in THC (total hydrocarbon) emissions when butanol is blended with biodiesel derived from rapeseed oil. The authors also reported that the addition of hydrogen as a combustion enhancer can be used to counteract the increase in THC emissions observed in butanol fuel blends.

Although diesel blended with butanol and WCO (waste cooking oil) has been extensively studied in the past, analyses of CBC formation from blends with additive levels as high as 50 vol.% biodiesel and 10% vol. butanol are not considerable. This study investigates the emission characteristics of a diesel generator fueled with blends of diesel/biodiesel/butanol. Overall, the objective is to study gaseous pollutants and CBCs produced by burning diesel fuels blended with butanol and WCO biodiesel in a diesel engine. The work is to evaluate the potential of blended fuels that is able to decrease CBC emissions from diesel engines. Further, the feasibility of biodiesel blends and optimum percentage of biodiesel in fuel blends are assessed.

2. Methods and materials

2.1. Test fuels preparation

The premium diesel fuel produced by Chinese Petroleum Corporation, Taiwan, is used as a base fuel in the current study. The waste cooking oil, which is the feedstock of the commercial neat biodiesel, is able to effectively reduce the raw material cost as well as solve the problem of waste oil disposal. The biodiesel from WCO (waste cooking oil) is produced by Greatek Green Energy Corporation and the butanol is obtained from J. T. Baker (>99.5% purity). Butanol produced by the fermentation of biomass is able to lower the cost of production and reduce the corrosive properties. The properties of the tested fuels are listed in Table 1. In this study, fuels with ten different blends are used. Blends of diesel/biodiesel are compared with blends of diesel/biodiesel/butanol in terms of fuel combustion emissions. Four of them are blended fuels B10–B40 (containing 10 vol%–40 vol% WCO biodiesel and 90 vol%–60 vol% diesel). The other five fuels are diesel blended with 10 vol% butanol and different levels of biodiesel contents (ranged from 10 to 40 vol%). A magnetic stirring plate is used to blend butanol in biodiesel.