Energy Conversion and Management 148 (2017) 251–259

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A parametric study on engine performance and emissions with neat diesel and diesel-butanol blends in the 13-Mode European Stationary Cycle

Md Nurun Nabi [a],*, Ali Zare [b], Farhad M. Hossain [b], Timothy A. Bodisco [c], Zoran D. Ristovski [b,d], Richard J. Brown [b]

[a] *School of Engineering and Technology, Central Queensland University, Perth 6000, Australia*
[b] *Biofuel Engine Research Facility, Queensland University of Technology (QUT), QLD 4000, Australia*
[c] *School of Engineering, Deakin University, Waurn Ponds, Victoria 3217, Australia*
[d] *ILAQH, Queensland University of Technology (QUT), QLD 4000, Australia*

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 16 May 2017
Accepted 1 June 2017

Keywords:
Diesel engine
ESC
n-Butanol
Performance and emissions parameters

ABSTRACT

This paper presents a comprehensive study of a wide range of engine performance parameters, including: indicated torque (IT), indicated power (IP), indicated mean effective pressure (IMEP) and indicated specific fuel consumption (ISFC). Further, the combustion parameters measured include: start of injection timing, in-cylinder peak pressure, boost pressure and rate of maximum pressure rise. Resultant emission parameters investigated include: exhaust blow by, unburned hydrocarbon (UBHC), oxides of nitrogen (NOx), particulate matter (PM), particle number (PN) and particle size distribution (PSD). Normal butanol (*n*-butanol) was chosen to blend with a reference diesel fuel. The experiment was conducted using a 6-cylinder, turbocharged common rail diesel engine in accordance with the 13-Mode European Stationary Cycle (ESC). Considering limits of solubility of *n*-butanol in reference diesel, a maximum of 30% *n*-butanol was blended with 70% reference diesel. Three different butanol blends having 10% butanol with 90% reference diesel, 20% butanol with 80% reference diesel and 30% butanol with 70% reference diesel (the blending percentages were on a volume basis) were prepared. The engine experimental results show that without considerably deteriorating engine performance, most of the emissions were significantly reduced with the butanol blends compared to those of the reference diesel.

1. Introduction

Oxygenated fuels, such as biodiesels and biofuels play an important role in reducing diesel emissions, especially diesel soot and PM emissions [1–5]. Kurtz et al. [6] performed experiments with two oxygenated fuels and reported a 91–97% reduction in PM emissions. Similarly, Rahman et al. [2] measured PM emissions from a common rail diesel engine running on biodiesel fuels with controlled chemical composition (carbon chain length) and therefore controlled oxygen content. The key finding of their investigation was that the reductions in the PM emission were entirely dependent on the oxygen content of the fuel. Savic et al. [7] have shown that the reduction in the PM emissions, with the increase in the oxygen content, is caused by a decrease in the primary soot particle size. Chen et al. [8] performed engine experiments with diesel and butanol blends. Their study showed that the use of diesel-butanol blends reduced soot emissions at all conditions. Lower NOx emissions at low loads were also demonstrated by the authors [8]. Maintaining high thermal efficiency, simultaneous NOx and soot reductions were obtained with the introduction of medium exhaust gas recirculation and high butanol/diesel ratio blends [9]. Altun et al. [10] did an experimental campaign with butanol-biodiesel blends and reported higher BSFC and thermal efficiency with butanol-biodiesel blends compared to those of biodiesel-diesel blends. In general, lower emissions, including CO, THC and NOx, were also reported by the authors for butanol-biodiesel blends. Sahin et al. [11] did experiments with *n*-butanol in a turbocharged diesel engine and reported lower smoke emissions. NOx emissions were slightly reduced with lower butanol blend but increased with higher butanol blends. Dogan et al. [12] performed experimental tests with *n*-butanol blends and reported increased brake specific fuel consumption, thermal efficiency and hydrocarbon emissions. However, lower CO, NOx and smoke

---

* Corresponding author.
E-mail address: m.nabi@cqu.edu.au (M.N. Nabi).

http://dx.doi.org/10.1016/j.enconman.2017.06.001
0196-8904/

opacity with butanol-diesel blends were observed. It is generally accepted that biofuels (biofuels are considered as oxygenated fuels) are still not economically viable and thus, if biofuels are to have a future, it is necessary to determine cost effective processes to produce them. Hoque et al. [13] produced biodiesels from low-cost feedstock including used cooking oil and animal fat by the well-established transesterification process. Glycerol is a by-product of biodiesel production and can be considered a promising low-cost bi-product for producing a wide range of chemicals [14]. Triacetin, a derivative of glycerol is considered to be a beneficial bio-additive [14]. Nabi et al. [15] and Zare et al. [16] did engine experiments with biodiesel and triacetin blends and reported significantly lower emissions including PM and PN emissions except NOx emissions.

Concerning the engine performance and emissions in a 13-Mode ESC, Liew et al. [17], performed engine experiments with H_2 as a supplemented fuel. Authors showed, higher NOx and NO_2 emissions, but lower NO emissions with the addition of 2% H_2. However, NOx, NO_2 and NO emissions were increased with the addition of 4% H_2. They also reported lower PM and CO emissions with the addition of H_2 under constant load. Jong et al. [18] conducted engine experiments to investigate the effect of Ethoxymethyl Tetrahydrofuran Ether (ETE) and Furfuryl Ethyl Ether (FEE) on engine performance and exhaust emissions under the 13-Mode ESC. Substantial reductions in PM and smoke emissions with ETE were reported by the authors. FEE also reduced soot emissions substantially with a penalty of higher NOx emission. Wang et al. [19] conducted experiments with a series of fuels including dimethyl carbonate, biodiesel and high cetane number diesel.

With concern over the depletion of natural resources, petroleum products and price hike of raw materials drive to explore renewable energy resources including biofuels [20]. Bio-butanol is becoming a popular fuel due to its renewable nature. However, detailed studies of engine performance parameters, gaseous emissions, particulate matter mass, number and size distributions with diesel-butanol blends are not well represented in the literature. In the current investigation, *n*-butanol was chosen for its renewable nature, being less hydrophilic, having a higher calorific value, lower vapour pressure, higher miscibility and a higher cetane number than that of ethanol [21]. After a careful and exhaustive search for the literature, no paper was found that conducted comprehensive parametric studies on engine performance and emissions with butanol-diesel blends on an ESC test. In this work, a thorough investigation of engine performance parameters and exhaust emissions with diesel and three diesel-butanol blends were conducted in an entirely instrumented 6-cylinder turbocharged common rail diesel engine.

The key objectives of this study were

- To investigate the influence of *n*-butanol addition to diesel fuel on engine performance and exhaust emissions in a 13-Mode European Stationary Cycle.
- To compare the engine performance and exhaust emissions results using butanol blends with those of reference diesel.

2. Materials and methods

All experiments were conducted with a precisely instrumented 6-cylinder common rail diesel engine. Some key engine specifications are given in Table 1, for more in-depth engine specific information, including the in-cylinder pressure acquisition system, refer to Ref. [22]. In accordance with the ESC 13-Mode, all measurements were done with three different speeds and the ESC prescribed loads. For each fuel tested, the engine was run at constant speed with five different loads including idle, 25%, 50%, 75% and 100%. It is widely accepted that the engine's maximum load at a certain speed is governed by the fuel types. Considering this fact, using each fuel, the maximum load was determined when the engine was run at full throttle at that speed. This load was considered as 100% load. Based on the nominal 100% load, the other loads were determined for each fuel at the prescribed engine speeds. The experimental set up is shown in Fig. 1. A fast aerosol mobility spectrometer DMS 500 (Cambustion Ltd.) was used for PN measurements. The raw exhaust was diluted in a dilution tunnel (partial flow). NOx emissions were measured with a CLD NOx analyser. Rahman et al. [2] conducted experiments with a series of fuels including biodiesel, with the same engine set up as the current study. The exhaust gas sampling system was described in detail in their study. A TSI DustTrak 8530 was used to measure the $PM_{2.5}$ emissions. The data from the DustTrak were converted into a gravimetric measurement using a tapered element oscillating microbalance (TEOM) for the DustTrak correlation of diesel particles [23]. Particle number and particle size distribution was measured with a DMS-500 (Cambustion Ltd), a fast particulate spectrometer without the heated sample line connected. To give outputs of particle size, number and mass in real time, the DMS500 combines electrical mobility measurements of particles with sensitive electrometer detectors. The experiment was conducted in accordance with the ESC protocol, where the engine was operated with 13 different modes. According to the ESC 13-Mode protocol, the engine speed was kept to ±50 rpm and the torque to ±2% of the maximum torque at the test speed. The dilution ratios for the 13-different modes were calculated with the raw and diluted CO_2 data and ranged from 2 to 24. The specific emissions were calculated by weighing with the ESC prescribed weighing factors. The details of the ESC operating conditions can be seen in Fig. 2 and Table 3. Considering the limitations of solubility of *n*-butanol in diesel, a maximum of 30 vol% *n*-butanol blend was prepared with 70 vol% reference diesel. In this study, three butanol blends were tested. The first blend is termed as Bu2 containing 10 vol% *n*-butanol and 90 vo% diesel (approximately 2% oxygen in the blend). Similarly, Bu4 contains 20 vol% *n*-butanol and 80 vol% diesel with 4% oxygen in the blend and Bu6 indicates 30 vol% *n*-butanol and 70 vol% diesel with 6% oxygen in the blend. The key fuel properties of reference diesel (D100), neat *n*-butanol (Bu100), Bu2, Bu4 and Bu6 are listed in Table 2. For neat *n*-butanol (Bu100), the properties including density, viscosity and higher heating value were taken from ref [24]. Based on the Bu100 and D100 properties in Table 2, the properties for other blends were calculated.

Table 1
Engine specifications.

Model	Cummins ISBe220 31
Number of cylinders	6 in-line
Capacity (L)	5.9
Bore × stroke (mm)	102 × 120
Maximum power	162 kW @ 2500 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
Emission standard	Euro III

3. Results and discussion

3.1. Engine performance parameters

In this section, different engine performance parameters with D100 and three *n*-butanol blends (Bu2, Bu4 and Bu6) are presented and discussed for the ESC test.