Impact of oxygenated additives to diesel-biodiesel blends in the context of performance and emissions characteristics of a CI engine

H.M. Mahmudul¹, Ftwi Y. Hagos¹,²*, Rizalman Mamat¹,² and Abdul A. Abdullah¹,²

¹Automotive Engineering Research Group (AERG), Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
²Automotive Engineering Center, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

E-mail: ftwi@ump.edu.my

Abstract. Butanol is receiving huge interest in the area of alternative fuel in the compression ignition (CI) engines. In this work, butanol is used as an oxygenated additive to diesel and biodiesel blend fuels to evaluate the performance and emission of CI engine. The commercially available pure diesel fuel (D100) and 80% commercially available diesel-biodiesel blend (5% biodiesel and 95% by volume) and 20% butanol (BU20) fuels were investigated to evaluate the effects of the fuel blends on the performance and exhaust emissions of a single cylinder diesel engine. The experiment was conducted at fixed load of 75% with the five engine speeds (from 1200-2400 rpm with an interval of 300 rpm). The engine performance parameters such as power, torque, fuel consumption and thermal efficiency and exhaust gas emissions such as nitrogen oxides, carbon monoxide, and exhaust gas temperature were analysed from the experimental data. The results shows that although butanol addition has caused a slight reduction in power and torque values (11.1% and 3.5%, respectively), the emission values of the engine were improved. With respect to the exhaust gas temperature, CO and NOx emissions, of BU20 is reported to have reduction by 17.7%, 20% and 3%, respectively than the B100. Therefore, butanol can be used as a fuel additive to diesel–biodiesel blends.

1. Introduction

The increasing of energy demand in power and transportation sectors along with the limitation of natural resources of fossil fuels and their negative effects on environments are the main motivations for researchers to search for an alternative fuels. Among the fuels, biodiesel plays an important role because it is renewable, less toxic and biodegradable [1]. Use of biodiesels may also delay the engine component life and can be used without any engine modification [2, 3]. Moreover, sometimes modification is suggested as their properties may contrast from petroleum-based diesel. Biodiesel can reduce the emission and therefore it is an attractive alternative. Moreover, strict emission regulations have contributed for the researchers to focus on the fuel or on the engine fuel-related modification.
techniques. Therefore, the development of oxygenated additive fuels can possibly meet the emissions regulations. The share of biodiesel is likely to increase in the automotive fuel markets in the years to come and a new regulation from (Directive 2009/28/EC) has set new targets that the European union members should use at least 10% renewable energy as fuel by 2020 [1, 4]. Malaysia is one of the major oil producer countries with an output of 18 million tons of crude palm oil every year. Though palm oil is the edible oil and large production of palm oil without hampering food chain can allow to use the oil in automotive fuel sectors. In order to enhance the biodiesel production, Malaysian government has allocated approximately 40% palm oil production into biodiesel industries [5, 6].

Researchers are using biodiesel in diesel engines with or without additives to solve the energy and environment issue. Kumar et al. [7] applied methanol in Jatropha oil and ethanol in animal fat to a diesel engine. The results showed that drastic reduction in smoke, NOx, HC and CO emissions with the emulsion as compared to neat fat and neat diesel at high power outputs. Hagos and Kumar have used ethanol as a fuel additive in the diesel-jatropha biodiesel blend. They have reported an improvement on the performance and emission as compared to the pure diesel [8]. Guarieiro et al. [9] used various blends of diesel and ethanol with soybean oil and biodiesel, castor oil and biodiesel, with 7% to 15% by volume ethanol was added. The authors have reported that an improvement of combustion efficiencies of diesel fuel can be achieved by the adding oxygenated fuels such as ethanol, biodiesel, and vegetable oils, due to having a complete combustion. However, there was no substantial difference in the case of CO emission [4]. Some researchers have reported that emissions were reduced when ethanol was used as an additive [10, 11].

Recent studies have shown that n-butanol, diesel, and palm biodiesel are among the biofuels that have the highest potential to function as fossil fuel additions and can be used easily as additives. With the increase in the percentage of renewable/oxygenated fuel in the blends, complete fuel combustion has been reported to be achieved [12]. Considering these technical merits, research on the simultaneous use of diesel, biodiesel, and alcohols in the form of ternary blends is attracting more attention, with the beneficial effects of the blends being upgraded fuel properties, engine performance, combustion characteristics, and more importantly exhaust emissions [8, 13-15]. Among alcohols, butanol has recently drawn particular attention as a renewable biofuel additive for diesel engines due to its higher heating value and cetane number, more miscibility with diesel, and less hydrophilic compared to methanol and ethanol [13, 16]. Recent studies suggest that butanol can be a better alternative biofuel than ethanol for use in CI engines [17]. Still, there is a lack of detailed investigations on the effects of butanol addition to diesel-biodiesel blends on engine performance and particulate emissions [18]. Therefore, this paper attempted to fill up this gap. The improved blends consisted of 75% diesel, 5% biodiesel, and 20% additive. The performance was analyzed in the context of indicated power (IP), indicated torque (IT), Indicated specific fuel consumption (ISFC) and indicated thermal efficiency (ITE). Regulated emissions, including exhaust gas temperature (EGT), NOx, CO, and CO\textsubscript{2} were also investigated and discussed from a comparative point of view, with BU20 as a baseline.

2. Methodology

The experiment was conducted at the engine test laboratory of the Automotive Engineering Center at University Malaysia Pahang, Pekan, Malaysia. The schematic view of the experimental setup of the engine is shown in Figure 1. A naturally aspirated water-cooled single-cylinder direct injection diesel engine was used to conduct the study. The specifications of the engine are shown in Table 1. A pressure transducer and crank angle encoder were used to collect the pressure reading at every crank angle degree and thereby to analyze the combustion characteristics. The engine was coupled with a positive displacement gear pump (model HGP-3A-F23) and it was used as a dynamometer. The data were recorded by the TFX Engineering DAQ system, which resided of the in-cylinder pressure
sensor, and crank angle sensor. The K-type thermocouples were used to measure the ambient temperature and the exhaust gas temperature which is connected to Pico thermocouple data logger.

The engine was run at different speeds ranging from 1200 to 2400 rpm and engine load of 75%. The hydraulic dynamometer was calibrated for the engine load. The fuel used in the investigation are D100 (100% diesel by volume) and BU20 (80% of the commercially available biodiesel blended diesel (95% diesel and 5% biodiesel) and 20% butanol by vol.). The alternative fuel (palm biodiesel) and the alcohol additive (butanol) were blended to the diesel fuel through stirring on a magnetic stirring plate and the properties of tested fuel are shown in Table 2. First, the engine was run using diesel fuel and carried out until the engine is in steady state condition. For every new experiment, the engine was run for sufficient time to consume the remaining fuel from the earlier experiment and was conducted very carefully and repeated for three times. A Kane (auto 5-2) exhaust gas analyzer is used for measuring the gaseous emissions such as CO, CO₂, and NOx. The Sensitivity and measurement accuracy of instruments used for measuring the exhaust gas concentration are shown in Table 3.

Figure 1. Schematic view of the experimental setup of engine
Table 1. Specifications for diesel engine:

| Description            | Specification                                                                 |
|------------------------|-------------------------------------------------------------------------------|
| Engine model           | TF120                                                                         |
| Engine type            | Horizontal, Compression ignition 4 stroke cycle                               |
| Combustion system      | Direct injection                                                              |
| Number of cylinders    | 1                                                                             |
| Bore x Stroke (mm)     | 92 x 96                                                                       |
| Displacement (L)       | 0.638                                                                         |
| Compression ratio      | 17.7                                                                          |
| Continuous output (HP) | 10.5 HP at 2400 RPM                                                          |
| Rated output (HP)      | 12 HP at 2400 RPM                                                            |
| Cooling system         | Water cooled (radiator type)                                                  |

Table 2: Basic fuel properties for diesel, biodiesel and butanol

| Fuel          | Lower heating value (MJ/kg) | Density@20°C (kg/m³) | Viscosity@40°C (mPa s) | Flash point(°C) | Cetane number |
|---------------|----------------------------|----------------------|------------------------|-----------------|--------------|
| Diesel        | 45.28                      | 853.8                | 2.6                    | 93              | 54.6         |
| Biodiesel(PME)| 41.3                       | 867                  | 4.53                   | 165             | 67           |
| Butanol       | 33.1                       | 808                  | 2.63                   | 35              | 25           |

Table 3: Exhaust gas analyser sensitivity and measurement accuracy.

| Exhaust gas | Measurements domain | Accuracy              |
|-------------|----------------------|-----------------------|
| NOx         | 0–1500 ppm           | ±5% or 25 ppm         |
| CO          | 0–10%                | ±5% or 0.06% vol_1    |
| CO₂         | 0–16%                | ±5% or 0.5% vol_1     |
| O₂          | 0–21%                | ±5% or 0.1% vol_1     |

3. Results and Discussion

The engine performance parameters such as power, torque, fuel consumption and thermal efficiency and exhaust gas emissions such as nitrogen oxides, carbon monoxide, and exhaust gas temperature were analysed from the experimental data. The pressure-volume data at every 1.0° crank angle was captured for consecutive 100 cycles with the help of the pressure transducer and the crank angle encoder. The cylinder pressure data was averaged over 100
cycles by obtaining mean cylinder pressure at each 1.0° crank angle interval according to the recommendations by Heywood [19]. The IMEP was calculated from the average cycle.

![Indicated Power](image1)

![Indicated Torque](image2)

![Indicated-specific fuel consumption](image3)

![Indicated thermal efficiency](image4)

**Figure 2.** Variation of performance with respect to speed of D100 and BU20 at fixed load

3.1 Engine Performance

3.1.1 Engine power and Torque. The variation of engine power and engine torque as a function of engine speed of diesel fuel D100 and the blended BU20 are shown in Figure 2 (a) and (b), respectively. It is shown that power and torque increased as the speed increased. The maximum power for D100 and BU20 are 7.6 kW and 6.2 kW, respectively. On the other
hand, the maximum torque for diesel D100 and BU20 are 25.6 Nm and 24.7 Nm, respectively. It is shown that the power of BU20 has decreased by 16%, 16.7%, 11.1%, 15.4% and 18.4% for the speeds 1200, 1500, 1800, 2100 and 2400 rpm, respectively while the torque by 25.8%, 14.9%, 9%, 3.7% and 3.5% than D100. This is attributed to the difference in heating value of the fuels. As shown in Table 2, the lower heating value of biodiesel and butanol approximately are lower by 8.78% and 26.89%, respectively as compared to diesel fuel. Moreover, the higher latent heat of vaporization of butanol creates a low gas temperature in combustion temperature which might be the reason for the reduction in lower power and torque [20, 21]. In addition, the other reasons for the decrease the performance of power and torque with diesel-biodiesel-butanol fuel blends are the low density and viscosity of butanol as well as its low cetane number.

3.1.2 Indicated Specific Fuel Consumption (ISFC). ISFC is the relation of total fuel flow mass consumption and the indicated power and correlations with fuel properties of viscosity, density, and heating values. Figure 2 (c) shown the ISFCs of pure diesel D100 and Biodiesel-diesel-butanol (BU20) blends at several engine speeds at 75% engine load. It is observed that the engine consumed the biodiesel-diesel-butanol blending BU20 higher than diesel fuel to produce corresponding power output for all test engine speeds. It was attributed that due to lower heating value and higher latent heat of vaporization of n-butanol [21, 22], with the increasing presence of n-butanol blends controlled to greater increase in the fuel consumption. Minimum ISFC was reported as 251.30, 206.92, 202.02, 194.68 and 199.39 g/kWh for diesel fuel at engine 1200, 1500, 1800, 2100 and 2400, respectively while the corresponding average ISFC for BU20 was 314.18, 268.4, 247.2, 246.6, 256.3 g/kWh, respectively. Lujaji et al. [18] have got the same trends in their experiment.

3.1.3 Indicated Thermal Efficiency (ITE). ITE is the ratio of power to the energy released during the combustion process. Figure 2(d) illustrates the comparison of ITEs of diesel fuel D100 and biodiesel diesel butanol as a function of different engine speeds. It can be seen that there are the differences with regards to ITE between pure diesel D100 and diesel-biodiesel butanol blending BU20. The reduction ITE of the BU20 were 15.3%, 12.7%, 8%, 11.5%, 12.5% at the corresponding engine speeds as compared to diesel fuel D100. It was attributed that to the lower heating value and the cetane number of butanol shown in Table 2 causes the lower exhaust gas temperature [23]. D100 obtained maximum ITE due to its lower ISFC and higher heating value than BU20.
3.2 Emission analysis

3.2.1 Exhaust Gas Temperature (EGT). Variations in exhaust gas temperatures are shown in Figure 3(a) of diesel fuel D100 and diesel-biodiesel-butanol blends as a function of different engine speeds. It was shown that the highest of exhaust gas temperature of D100 was obtained 248.9, 256, 280.3, 349.1, 415.9°C in the range of 1200-2400 rpm. Moreover, the exhaust gas temperature measured by BU20 decreased 17.7, 12.8, 6.24 and 1.3%, respectively than D100. The existence of more amount of oxygen in the chemical structure of n-butanol may cause a significant cooling effect of the fuel spray patterns leading to longer

Figure 3. Variation of emissions with respect to speed of D100 and BU20 at fixed load
ignition delay, causing incomplete combustion and lower exhaust gas temperatures. Also, it is supported by Rakopolos et al. [24] showed that n-butanol produces a lower exhaust gas temperature because the engine runs overall leaner due to the oxygen content of the fuel additives.

3.2.2 Carbon monoxide (CO). Figure 3(b) shows the variations of CO emissions of D100 and BU20 at different engine speeds. Generally, biodiesel contains additional oxygen and this additional oxygen improves the complete combustion and reduces the CO emissions. The CO emissions of BU20 has decreased by 8.3%, 20%, 12.5% and 1.96% for the engine speeds of 1200, 1500, 1800 and 2100 rpm, respectively. At 2400 rpm, however, the CO emission of BU20 is observed to be higher than that of D100. The reason of decrease is mainly due to the oxygen content. In contrast to BU20; butanol addition to diesel-biodiesel blend further decreased CO emissions. This benefit in CO emissions using alcohols blends was also acknowledged by Skujit et al. attributing it the lower C/H ratio of alcohols compared to D100 [17]. With regard to most of the other authors, also a decrease in CO emissions occurs when substituting diesel-biodiesel-alcohol [25, 26]. The reason for the reverse in the trend at 2400 rpm could be due to the higher latent heat of vaporization leading to decreased in combustion temperature.

3.2.3 Nitrogen oxides (NOx). The NOx emission values variation for D100 and BU20 is presented at different engine speeds in Figure 6. NOx formation is extremely related to the combustion temperature and all engine operating conditions, such as engine speed, engine load, and fuel to Air (F/A) ratio. NOx emissions decreased when butanol was applied in diesel-biodiesel blending BU20, in comparison to diesel D10 at all engine speeds. The reduction in NOx emissions of BU20 was reduced by 10.4, 25.3, 23.9, 29.4 and 8.4%, respectively in the range of 1200-2400 rpm than the pure diesel. This may be attributed due to its lower calorific value and its higher heat of evaporation of butanol. Besides, the higher oxygen content with butanol has lead to lean engine operation condition as compared to diesel with the same fuel content charged in the engine. [24]. Ozsezen et al. [27] also show a decrease of NOx emission butanol addition.

Conclusions
The experiment was conducted in a single cylinder diesel engine. From the experiment, the engine performance and emissions were investigated by using diesel-palm biodiesel and butanol blends. The following are major concluding remarks from the stud:

- The engine performances showed that using butanol addition in diesel-biodiesel blendings the power, torque, and thermal efficiency reduced slightly than pure diesel D100.
The indicated specific fuel consumption of BU20 slightly increased than D100. The exhaust emission study indicated that CO and NOx emission improved with butanol addition.

In conclusion, the overall improvement on the NOx and CO in all engine condition makes butanol to be promising additive to diesel–biodiesel blends and can be used in the engine without any engine modification. However, the drop on the performance over the wider range of operation trigers cation over the use of this additive in particular on the view of the storage capacity of the automotive vehicles.

Acknowledgement

The authors would like to acknowledge the financial support by Universiti Malaysia Pahang under the internal grant RDU 150341 and the postgraduate research fund PGRS160304 and the Ministry of Higher Education (MOHE) with project number FRGS/1/2015/TK07/UMP/02/2 (RDU150124).

References

[1] S. Intenan, H. Masjuki, M. Varman, M. Kalam, M. Arbab, H. Sajjad, and S. A. Rahman, “Impact of oxygenated additives to palm and jatropha biodiesel blends in the context of performance and emissions characteristics of a light-duty diesel engine,” Energy Conversion and Management, vol. 83, pp. 149-158, 2014.
[2] A. L. Boehman, “Biodiesel production and processing,” Fuel Processing Technology, vol. 86, no. 10, pp. 1057-1058, 2005.
[3] Z. Helwani, M. Othman, N. Aziz, W. Fernando, and J. Kim, “Technologies for production of biodiesel focusing on green catalytic techniques: a review,” Fuel Processing Technology, vol. 90, no. 12, pp. 1502-1514, 2009.
[4] D. Rakopoulos, “Combustion and emissions of cottonseed oil and its bio-diesel in blends with either n-butanol or diethyl ether in HSDI diesel engine,” Fuel, vol. 105, pp. 603-613, 2013.
[5] M. Mofijur, H. Masjuki, M. Kalam, and A. Atabani, “Evaluation of biodiesel blending, engine performance and emissions characteristics of Jatropha curcas methyl ester: Malaysian perspective,” Energy, vol. 55, pp. 879-887, 2013.
[6] A. Aziz, W. C. Siong, R. Mamat, and F. Y. Hagos, “Exhaust Emission Reduction of Diesel Engine Fueled with Emulsified Palm Oil Methyl Esters.” pp. 457-461.
[7] M. S. Kumar, A. Ramesh, and B. Nagalingam, “An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine,” biomass and bioenergy, vol. 25, no. 3, pp. 309-318, 2003.
[8] F. Y. Hagos, and N. Kumar, “Fuelling a Small Capacity Algricultural Unmodified Diesel Engine with Macro-emulsified Ethanol, Diesel and Jatropha Derived Biodiesel: Performance & Emission Studies.” pp. 835-842.
[9] L. L. N. Guarieiro, E. T. de Almeida Guerreiro, K. K. dos Santos Amparo, V. B. Manera, A. C. D. Regis, A. G. Santos, V. P. Ferreira, D. J. Leão, E. A. Torres, and J. B. de Andrade, “Assessment of the use of oxygenated fuels on emissions and performance of a diesel engine,” Microchemical Journal, vol. 117, pp. 94-99, 2014.
[10] P. Kwanchareon, A. Luengnaruemitchai, and S. Jai-In, “Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine,” Fuel, vol. 86, no. 7–8, pp. 1053-1061, 5/6, 2007.
[11] N. Vedaraman, S. Puhan, G. Nagarajan, and K. Velappan, “Preparation of palm oil biodiesel and effect of various additives on NOx emission reduction in B20: An experimental study,” International Journal of Green Energy, vol. 8, no. 3, pp. 383-397, 2011.
[12] C. Guido, C. Beatrice, and P. Napolitano, “Application of bioethanol/RME/diesel blend in a Euro5 automotive diesel engine: potentiality of closed loop combustion control technology,” *Applied Energy*, vol. 102, pp. 13-23, 2013.

[13] E. Sukjit, J. Herreros, J. Piaszyk, K. Dearn, and A. Tsolakis, “Finding synergies in fuels properties for the design of renewable fuels–Hydroxylated biodiesel effects on butanol-diesel blends,” *Environmental science & technology*, vol. 47, no. 7, pp. 3535-3542, 2013.

[14] Y. Yoshimoto, E. Kinoshita, L. Shanbu, and T. Ohmura, “Influence of 1-butanol addition on diesel combustion with palm oil methyl ester/gas oil blends,” *Energy*, vol. 61, pp. 44-51, 2013.

[15] D. B. Hulwan, and S. V. Joshi, “Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel–ethanol–biodiesel blends of high ethanol content,” *Applied Energy*, vol. 88, no. 12, pp. 5042-5055, 2011.

[16] S. Altun, C. Oner, F. Yasar, and H. Adin, “Effect of n-butanol blending with a blend of diesel and biodiesel on performance and exhaust emissions of a diesel engine,” *Industrial & Engineering Chemistry Research*, vol. 50, no. 15, pp. 9425-9430, 2011.

[17] E. Sukjit, J. Herreros, K. Dearn, R. García-Contreras, and A. Tsolakis, “The effect of the addition of individual methyl esters on the combustion and emissions of ethanol and butanol-diesel blends,” *Energy*, vol. 42, no. 1, pp. 364-374, 2012.

[18] F. Lujaji, L. Kristóf, A. Bereczky, and M. Mbarawa, “Experimental investigation of fuel properties, engine performance, combustion and emissions of blends containing croton oil, butanol, and diesel on a CI engine,” *Fuel*, vol. 90, no. 2, pp. 505-510, 2011.

[19] J. Heywood, *Internal Combustion Engine Fundamentals*, pp. 930: McGraw-Hill Education, 1988.

[20] D. Qi, C. Bae, Y. Feng, C. Jia, and Y. Bian, “Combustion and emission characteristics of a direct injection compression ignition engine using rapeseed oil based micro-emulsions,” *Fuel*, vol. 107, pp. 570-577, 2013.

[21] A. Atmanlı, E. İleri, and B. Yüksel, “Effects of higher ratios of n-butanol addition to diesel–vegetable oil blends on performance and exhaust emissions of a diesel engine,” *Journal of the Energy Institute*, vol. 88, no. 3, pp. 209-220, 2015.

[22] C. Rakopoulos, A. Dimaratos, E. Giakoumis, and D. Rakopoulos, “Study of turbocharged diesel engine operation, pollutant emissions and combustion noise radiation during starting with bio-diesel or n-butanol diesel fuel blends,” *Applied Energy*, vol. 88, no. 11, pp. 3905-3916, 2011.

[23] D. Rakopoulos, C. Rakopoulos, E. Giakoumis, A. Dimaratos, and D. Kyritsis, “Effects of butanol–diesel fuel blends on the performance and emissions of a high-speed DI diesel engine,” *Energy Conversion and Management*, vol. 51, no. 10, pp. 1989-1997, 2010.

[24] C. D. Rakopoulos, A. M. Dimaratos, E. G. Giakoumis, and D. C. Rakopoulos, “Investigating the emissions during acceleration of a turbocharged diesel engine operating with bio-diesel or n-butanol diesel fuel blends,” *Energy*, vol. 35, no. 12, pp. 5173-5184, 2010.

[25] G. Tüccar, T. Özgür, and K. Aydın, “Effect of diesel–microalgae biodiesel–butanol blends on performance and emissions of diesel engine,” *Fuel*, vol. 132, pp. 47-52, 2014.

[26] O. Doğan, “The influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions,” *Fuel*, vol. 90, no. 7, pp. 2467-2472, 2011.

[27] A. N. Ozsezen, A. Turkcan, C. Sayin, and M. Canakci, “Comparison of performance and combustion parameters in a heavy-duty diesel engine fueled with iso-butanol/diesel fuel blends,” *Energy Exploration & Exploitation*, vol. 29, no. 5, pp. 525-541, 2011.