AN INVESTIGATION OF USING PALM BIODIESEL BLEND ON THE PERFORMANCE OF A STATIONARY MARINE DIESEL ENGINE

Che Wan Mohd Noor[1, 2*], Rizalman Mamat[1], Wan Mohd Norsani[2] & Muhamad Mat Noor[1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang (UMP), Malaysia
[2]School of Ocean Engineering, Universiti Malaysia Terengganu (UMT), Malaysia

[*]Email: che.wan@umt.edu.my

ABSTRACT

Most of marine vehicles use petroleum based fuel as the source of energy in their daily operations. However, volatile oil price and concerns over depletion of petroleum resources have hastened researchers to look for other alternative fuel. As a result, biodiesel has been identified as one of the environmentally friendly alternatives energies and at the same time can reduce our dependency on petroleum-based fuels. The present study investigates the effects of palm biodiesel blends on stationary marine diesel engines with regards to the engines' performance characteristics, such as brake power, brake specific fuel consumption, exhaust gas temperature, brake thermal efficient and NO_X *emissions. The experiment was conducted using Cummins NT-855 marine diesel engines. The results revealed that the use of palm biodiesel blends increased the brake specific fuel consumption,* NO_X *emissions and exhaust gas temperature up to 18.75%, 26.15% and 5.5% respectively. On the other hand, it contributed to reduced brake thermal efficiency by 12.17%. On one hand, palm biodiesel does not give any significant difference in engine brake power when compared to petroleum diesel. On the whole, it is proved that low blend palm biodiesel can be used in marine diesel engines, thereby providing a viable alternative to petroleum diesel.*

Keywords: *Palm biodiesel; marine diesel engine; engine performance; emission.*

1. INTRODUCTION

Most modern ships use marine diesel engine as their prime mover due to their operating simplicity, robustness and fuel economy as compared to most other propulsion mechanisms. In fact, marine engines are very similar to the self-ignition engines in heavy-duty vehicles but they are generally larger, more complex, and operate with higher efficiency (Palocz-Andresen, 2013). Marine engines provide major power sources for sea transportation and contribute to the prosperity of the worldwide economy. The most types of marine fuel are marine diesel oil (MDO) and heavy fuel oil (HFO). which are derived from petroleum distillation. However, the volatility of crude oil prices lately and concerns over the depletion of fossil fuel reserves have forced researchers to look for other alternative fuels (Ashraful *et al*., 2014; López *et al*., 2015). As a result, biodiesel has gained a growing interest as one of the most promising solutions for these issues. Biodiesel is considered as a better option as it is renewable and eco-friendly as compared to fossil fuels. Its primary advantages are that it is biodegradable, renewable, sulphur-free and does not produce hazardous toxic gases (Demirbas, 2009). Biodiesel is briefly defined as the monoalkyl esters of vegetable oils or animal fats. It can be produced from a great variety of feedstocks, which include most common vegetable oils (e.g., soybean, cottonseed, palm, peanut, rapeseed, canola, sunflower, safflower, coconut) and animal fats as well as waste oils (Knothe *et al*., 2005). The process used to convert this feedstock to biodiesel is called *transesterification* where the vegetable oil or animal fat is subjected to the chemical reaction. Fuel properties and combustion characteristics of biodiesel are similar to those of petroleum-derived diesel, which means that biodiesel can be used as an alternative fuel in any proportion without requiring any engine modification (Demirbas, 2005, 2009; Shojaeefard *et al*., 2012; Cirak & Demirtas, 2014; Chong *et al*., 2015).

In recent years, biodiesel from palm oil and jatropha has been identified as renewable energy source with huge potential in the future (Mekhilef *et al*., 2011). Palm biodiesel has been chosen for the current study because Malaysia is one of the world's leading palm oil producers. Most of its agricultural land is used for palm oil plantations. Oil palm planted area in 2015 reached 5.64 million ha, an increase of 4.6% as against 5.39 million ha recorded in the previous year (Malaysian Palm Oil Board, 2016). The palm oil harvested and produced from palm trees is referred to as crude palm oil (CPO). The oil is converted into biodiesel or palm methyl ester (PME) by the *transesterification* process using methanol as a catalyst. In order to encourage the use of palm oil biodiesel in industrial sectors in Malaysia, the National Biofuel Policy (NBP) was launched in August 2005 to promote the use of sustainable energy sources including biodiesel and biomass with support in terms of subsidized prices for the industry (Ministry of Plantation Industries and Commodities Malaysia, 2006). Since 2011, the B5 biodiesel (5% PME blend with 95% petroleum) was made available throughout the country and as for early 2016, B7 palm biodiesel (7% PME blend with 93% petroleum diesel) has been sold in the domestic market, especially for road vehicles (Chin, 2011).

Numerous studies on the application of biodiesel on diesel engines have been carried out and the results have shown that the performance of engines is comparable to that of using petroleum diesel fuel (Xue *et al*., 2011; Roy *et al*., 2014; Rizwanul Fattah et al. 2014; Wan Nor Maawa *et al*., 2015; Rakopoulos *et al*., 2015; Iqbal *et al*., 2015; Senthilkumar *et al*., 2015; Yasin *et al*., 2015; Ali *et al*., 2016; Monirul *et al*., 2016; Rashed *et al*., 2016;). These results are mostly obtained from laboratory experiments conducted on automotive or land-based diesel engines. The application of biodiesel on marine engines also has been explored by some researchers. A series of experiments was carried out by Murillo *et al*. (2007) on four-stroke, direct injection and naturally aspirated single cylinder outboard marine engines. They investigated the effect of different proportions of biodiesel that was derived from waste cooking oil to measure engine performance and emissions. The test fuels involved were pure diesel (B0), 10% biodiesel, 90% diesel (B10), 30% biodiesel, 70% diesel (B30), 50% biodiesel, 50% diesel (B50) and pure diesel (B100). The authors reported the test biodiesel reduces the brake power, in the extreme case of pure biodiesel (B100) up to 7.14% of the rated power. They claimed that waste cooking oil biodiesel also improved the emission of CO which up to 12%. On the other hand, there were increases in specific fuel consumption (about 11.4%) and brake thermal efficiency. The author addressed that the reason may be related to the atomisation of the blend during injection or with the stability of the mixtures of fuels during storage, pumping and injection.

Another study using the same biodiesel feedstock was conducted by Roskilly *et al*. (2008) on marine engine on-board ships. The tests were performed on a Perkins 404C-22 engine in Ship No. 1 and a Nanni Diesel engine 3.100HE in Ship No. 2. The result showed that biodiesel increased brake specific fuel consumption (BSFC) by 8.6-20.9% for both marine engines. The author identified this as mainly due to the lower gross heating values of biodiesel (39.62– 39.66 MJ/kg) compared with that of petroleum diesel (45.00 MJ/kg). The exhaust temperatures were a little higher when fuelled with biodiesel, ranging from 1.8% to 11.5% for both engines. Engine output powers for both tested engines were nearly equal with the difference of less than 1% on the whole test range. However, interestingly the author found that biodiesel reduced the NO_X emission up to 24.3%. These results contradicted with Murillo *et al*. (2007). They suggested that the reason for this reduction is due to smaller heating values and the higher Cetane number of biodiesel. Early studies on a Wärtsilä marine diesel engine using palm biodiesel was reported by Juoperi (2008). The results indicated a slight increase in NO_X, and a reduction of CO and HC exhaust emissions. More recently, Lin (2014) examined the effects of blending fishing boat fuels with various weight proportions of waste cooking oil biodiesel. The results showed that biodiesel blending can significantly improve the inferior fuel properties such as increasing in flash point and a reduction in sulphur content. However, the author reported that biodiesel blending caused a slight decrease in heating value around 1–4.5%.

It should be noted from the above literature that there are limited researches on marine diesel engines with palm biodiesel have been reported so far, and this has motivated the present study. Furthermore, the existence of the Malaysian national biofuel policy has increased the exploration of biodiesel research related to resources available in the country. Therefore, it is a great interest for the authors to investigate the effects of palm biodiesel on the marine diesel engine with regards to the engines' performance and emission characteristics. The authors hope that this paper can provide useful information to researchers, engineers, marine industry players and those interested in biodiesel as an alternative energy source rather than rely solely on fossil fuels.

2. EXPERIMENTAL SETUP

In this study, the experiments were performed on a stationary Cummins NT-855 marine diesel engine. The details of engine specification are presented in Table 1. Full setup of marine diesel engine is shown in Figure 1, where 250 kW eddy-current dynamometer was attached to the engine in order to measure engine brake power and torque. Fuel consumption and air flow rate was measured by positive displacement type KOBOLD flowmeter and TAYLOR air flowmeter respectively. The engine was equipped with K-type thermocouples and resistance temperature detectors (RTD) with cover temperature range from -40 ^{o}C to 1200 ^{o}C for temperature measurement. All the required data were collected through REO-DCA data acquisition unit as shown in Figure 2. The whole schematically diagram of experimental setup is given in Figure 3

Table 1: Marine diesel engine specifications.

Brand/Model	Cummins NT-855
Engine type	4 cycle-Inline-6 cylinder
Bore x stroke	139 mm x 152 mm
Displacement volume	14 liter
Compression ratio	14.5
Maximum torque	1068 N.m
Maximum power	201 kW
Cooling system	Water cooling

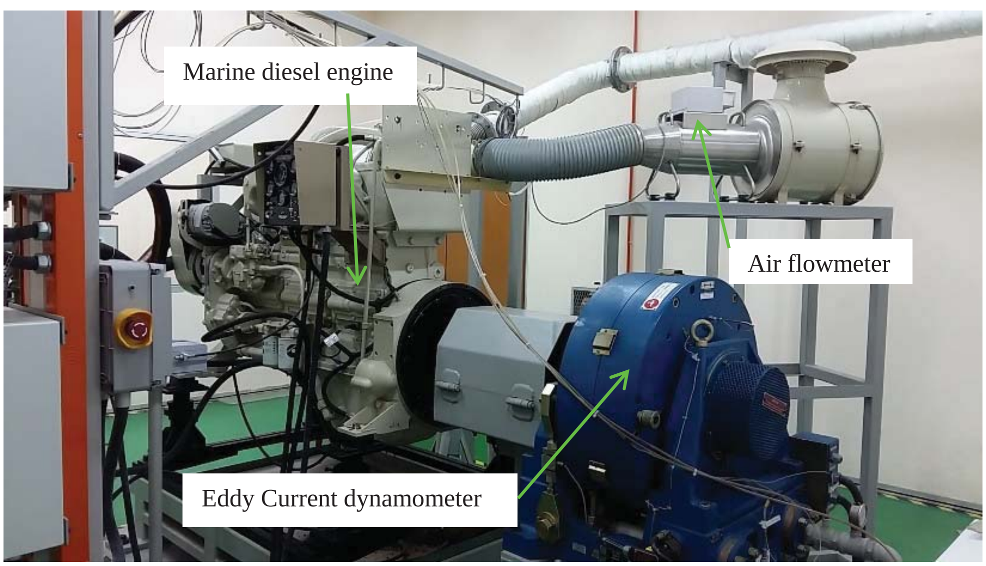

Figure 1: Full setup of marine diesel engine.

.

Figure 2: REO-DCA data acquisition unit.

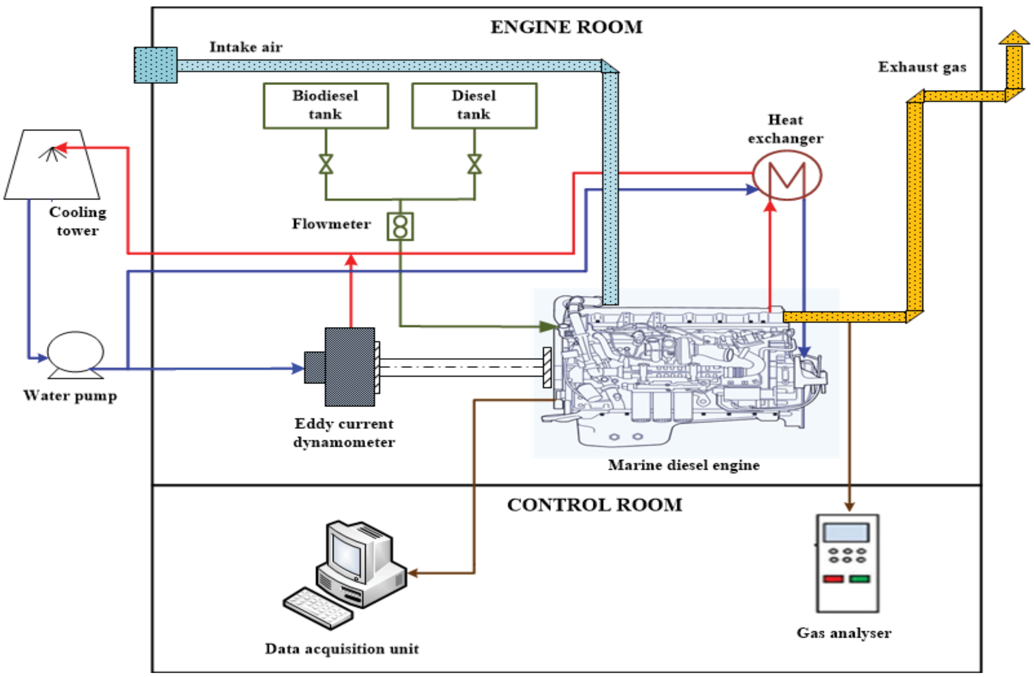

Figure 3: Schematic diagram of the experimental setup.

The experiments were carried out using low percentage of palm biodiesel blend such as B0 (100% petroleum diesel), B5 (5% biodiesel + 95% petroleum diesel), B10 and B15. The blend samples were prepared by mixing petroleum diesel with certified palm oil biodiesel. The blended fuel samples are shown in Figure 4. Basic properties of all tested fuels were measured and summarised in Table 2. Engine performance tests were performed under steady-state condition at three different engine loads (10%, 30% and 50%) and constant speeds of 1600 rpm. Before each test, the engine was warmed up for about 15 minutes until the cooling water temperature stabilized. Desired parameters such as engine speeds, torque, brake power, exhaust gas temperature and fuel consumption were recorded, while brake specific fuel consumption, brake thermal and volumetric efficiency were computed later. All tests were completed without any modifications on the test engine.

Figure 4: Biodiesel blend fuel samples.

Table 2: Basic properties of palm biodiesel fuel blends.

Fuel properties	B0	B5	B10	B15	B100
Heating value (MJ/kg)	48.26	46.87	46.33	45.47	42.07
Density @ 15 ^{o}C (kg/m^3)	813	815	818	820	854
Kinematic viscosity @ 40 ^{o}C (cst)	4.02	4.15	4.52	4.60	5.66
Flash point (^{o}C)	70	104	110	113	180
Cetane number	46	47	48	49	57

3. RESULTS AND DISCUSSION

3.1 Brake Power

Brake power is the measurement of an engine's horsepower before the loss in power caused by the gearbox, alternator, water pump, and other auxiliary components. Brakes refer to a device used to load an engine and hold it at a desired engine speed. During testing, the output torque and rotational speed can be measured to determine the brake horsepower which is the actual shaft horsepower and is measured by using dynamometer. Figure 5 illustrates the brake power of the marine diesel engine running with palm biodiesel blends with respect to three engine loads (10%, 30% and 50%) and at constant engine speed of 1600 rpm. Since the amount of injected liquid fuel increased with engine load, the engine power rose by increasing engine load for all tested fuels. The brake power at 10% engine load for B0, B5, B10, and B15 were 17.0 kW, 18.0 kW, 17.4 kW and 17.7 kW respectively. These values were increased to 83.9 kW, 83.9 kW, 83.8 kW and 82.9 kW at half load (50%) condition. Meanwhile, the results show that there are no significant differences in the measured engine power output between petroleum diesel and biodiesel blends for each load tested except some drop for B10 fuel at 30% engine load. According to (Xue et al. 2011) about 22% of previous finding stated that biodiesel produced similar power output compared to diesel. In this study, all tested palm biodiesel blends produced almost the same output power compare to diesel, thus this indicate that palm biodiesel blend can be used for marine diesel engines without scarifies any reduction of engine brake power.

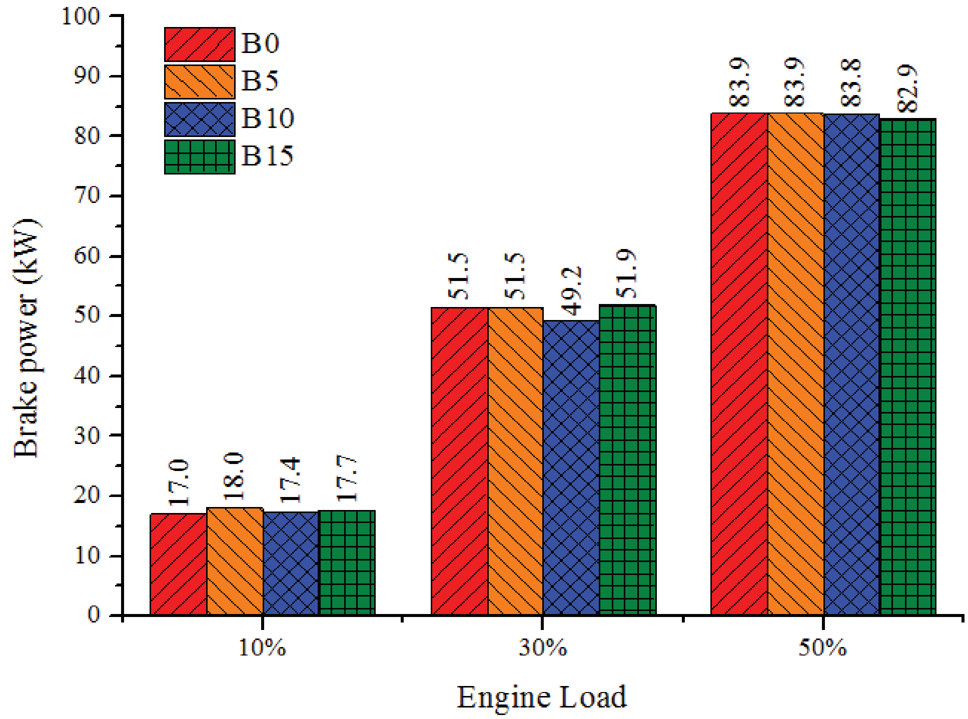

Figure 5: Brake power at various engine loads.

3.2 Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) is defined as the fuel consumption rate divided by its corresponding engine brake power output. It is desirable to obtain a lower value of brake specific fuel consumption meaning that the engine used less fuel to produce the same amount of work. The variations of BSFC with engine load for B0, B5, B10 and B15 are shown in Figure 6. BSFC, in general, was found to be decrease with an increasing of engine loads in all blends. One possible reason for this trend could be where increase percentage of required fuel in engine operation is less than the increase percentage of brake power due to relatively less portion of the heat losses at higher load. On the other hand, the increase proportion of biodiesel in tested fuel has raised BSFC value which means more amount of fuel required for the same operation. Maximum raised of fuel consumption which is about 18.75% was noticed at 10% engine load when compared to petroleum diesel. The blend with higher biodiesel content consumed more by the engine as it needed to compensate the loss of heating value in biodiesel (Shojaeefard et al. 2012). Therefore, the amount of fuel introduced to the cylinder for a desired energy input has to be greater with the biodiesel blends. Furthermore, higher containments of oxygen in biodiesel are also the cause of the lower heating value. Despite the better combustion of biodiesel compared to the petroleum diesel, the oxygen in biodiesel takes up space in the blend and slightly increases the fuel consumption rate. The increasing of BSFC with palm biodiesel mixture in diesel engine was consistent with findings of past studies by (Monirul et al. 2016; Rizwanul Fattah et al. 2014; Rashed et al. 2016; Ali et al. 2016; Murillo et al. 2007; Roskilly et al. 2008).

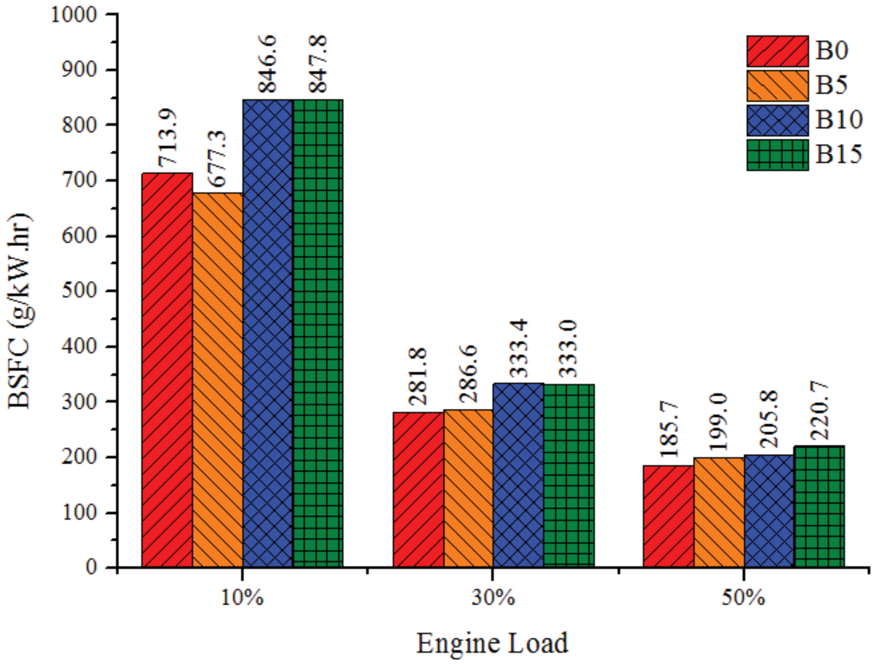

Figure 6: Brake specific fuel consumption various engine loads.

3.3 Exhaust Gas Temperature

The variations of exhaust gas temperature (EGT) of marine diesel engine, when operated with diesel-biodiesel blends at three different engine loads, are shown in Figure 7. EGT was found to be increase with the increase in both concentrations of palm biodiesel in the blends and engine load. At 10% engine load conditions, EGT was 158.9 ^{o}C, 160.6 ^{o}C, 160.3 ^{o}C and 167.5 ^{o}C with B0, B5, B10 and B15 respectively, whereas it was increased to 277.6 ^{o}C, 278.4 ^{o}C, 278.1 ^{o}C and 280.4 ^{o}C at 50% engine loading. The increase in EGT with engine load is obvious from the simple fact that the higher amount of fuel was required in the combustion chamber in order to generate extra power needed to take up additional loading. Palm biodiesel blend has slightly contribute to the increasing of EGT when compare to petroleum diesel which is observed less than 5.5% increment for all engine load conditions. This phenomenon is due to high oxygen content in palm biodiesel which contribute to more amounts of heat to be reclaimed during combustion process. Most of biodiesel will slightly increase in EGT (Kumar & Chauhan 2013).

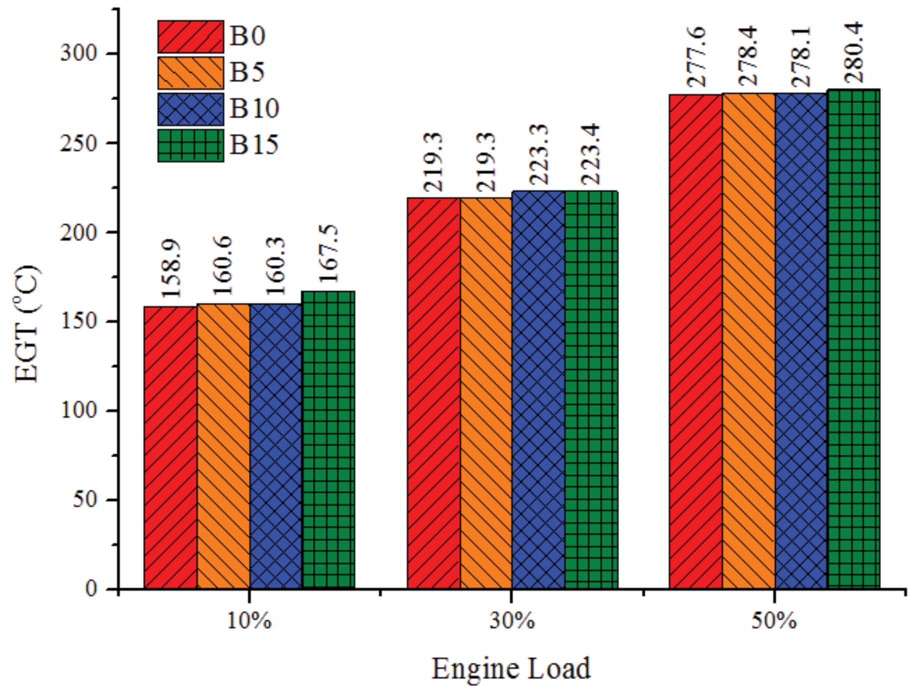

Figure 7: Exhaust gas temperature at various engine loads.

3.4 Brake thermal efficiency

Brake thermal efficiency (BTE) is used to evaluate how well an engine converts heat from supplied fuel to mechanical energy. This parameter is determined by dividing the brake power of the engine to the amount of energy input to the system. The amount of energy which cannot be converted into mechanical energy is discharged by the system through friction losses, heat transfer through the engine cylinder and exhaust gases. BTE of marine diesel engine, when operated with diesel-biodiesel blends at different engine loads, has been plotted in Figure 8. At 10% engine loading, brake thermal efficiency values were found to be 10.4%, 11.3%, 9.2% and 9.3% with B0, B5, B10, and B15, respectively, which were increased to 39.8%, 38.6%, 37.8% and 35.9% at half load (50%) condition. The BTE improved with the increasing engine load for the main reason that a relatively less portion of the power was lost at higher loads. The figure also indicates that BTE reduced when increase palm biodiesel percentage in blended fuel, which is up to 12.17% reduction. The decreasing of BTE is due to higher density and viscosity value of palm biodiesel compared to petroleum diesel (Öztürk 2015). This will reduced the atomization and vaporization of biodiesel blends fuel which producing uneven combustion characteristics compared with diesel (Banapurmath et al. 2008).

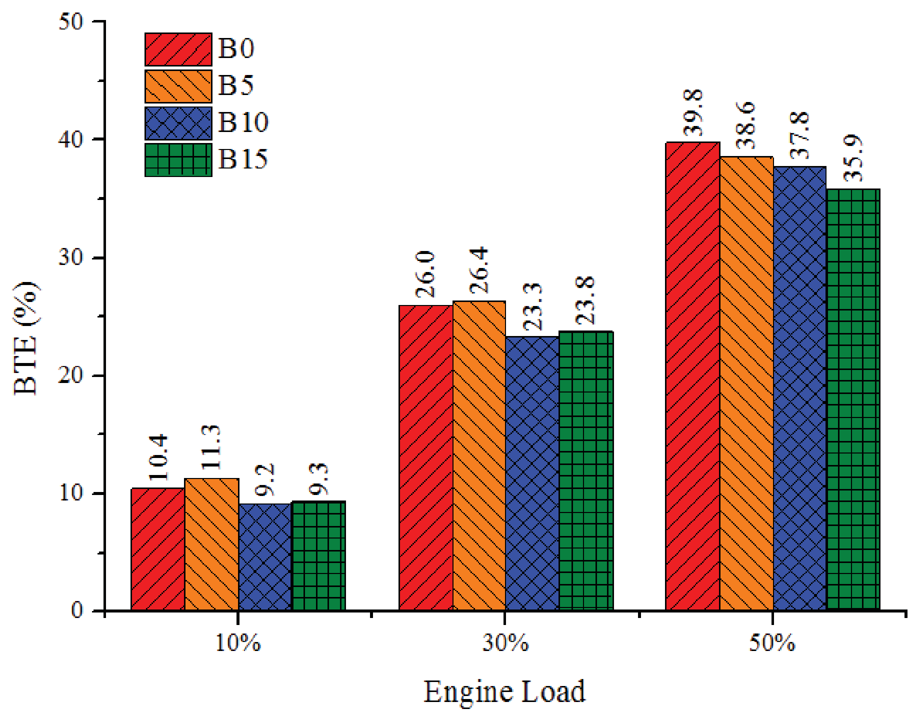

Figure 8: Brake thermal efficiency at various engine loads.

3.5 Nitrogen Oxide Emissions (NOx)

NO_X emissions are resulted from combustion process when nitrogen and oxygen are present at elevated temperatures in engine cylinder (Can 2014). Kinetics of NO_X formation is governed by Zeldovich mechanism and its formation is highly dependent on temperature and availability of oxygen (Heywood 1988). Figure 9 shows the effect of biodiesel blend on NO_X emission at three different engine loads. It is found that NO_X emissions increased up to 26.15% when more percentage of palm biodiesel added in blends. This result correlates with a slightly higher EGT with biodiesel. Biodiesels contain higher oxygen component (Roskilly et al. 2008; Öztürk 2015; Palash et al. 2013), thus it is evident that there is higher oxygen content will react with the nitrogen component from intake air, resulting in extra NO_X formation. Fattah et al. state that NO_X will increases with palm methyl ester content in blend (Rizwanul Fattah *et al*., 2013).

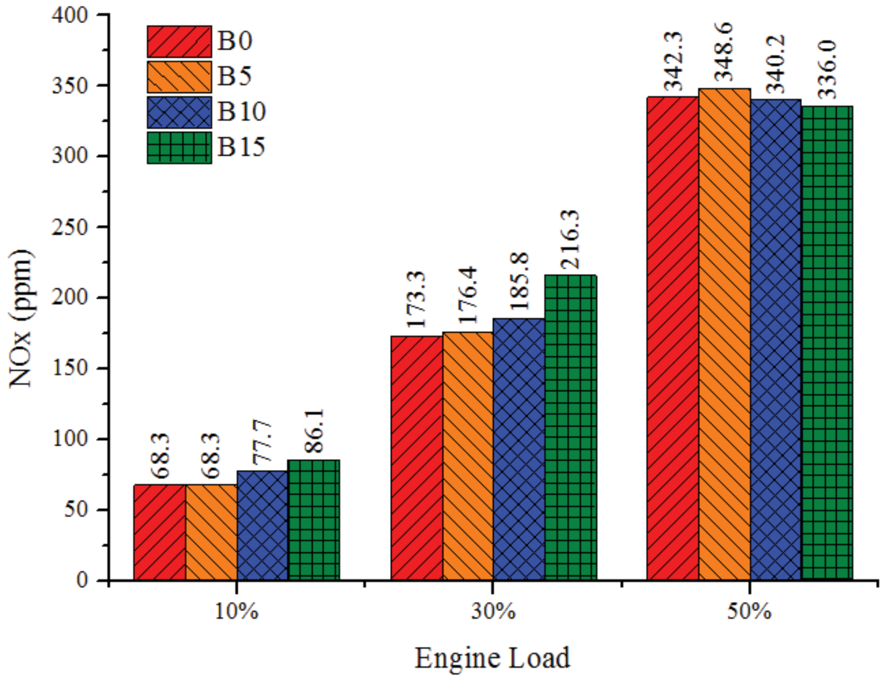

Figure 9: Nitrogen oxide emissions at various engine loads.

REFERENCES

Ali, O.M., Mamat, R., Abdullah, N.R. & Abdullah, A.A. (2016). Analysis of blended fuel properties and engine performance with palm biodiesel-diesel blended fuel. *Renew. Energ.*, **86**: 59–67.

Ashraful, A.M., Masjuki, H.H., Kalam, M.A., Rizwanul Fattah, I.M., Imtenan, S., Shahir, S.A. & Mobarak, H.M. (2014). Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review. *Energ Conversion and Management*, **80**: 202–228.

Banapurmath, N.R., Tewari, P.G. & Hosmath, R.S. (2008). Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methyl esters. *Renew. Energ.*, **33**:1982–1988.

Can, Ö. (2014). Combustion characteristics, performance and exhaust emissions of a diesel engine fueled with a waste cooking oil biodiesel mixture. *Energ. Convers. Manage.*, **87**: 676–686.

Chin, M. (2011). Biofuels in Malaysia: An analysis of the legal and Infrastructural frame work. *Working Paper*, pp.23–35.

Chong, C.T., Ng, J.H., Ahmad, S. & Rajoo, S. (2015). Oxygenated palm biodiesel: Ignition, combustion and emissions quantification in a light-duty diesel engine. *Energy Convers. Manage.*, **101**: 317–325.

Cirak, B. & Demirtas, S. (2014). An application of artificial neural network for predicting engine torque in a biodiesel engine. *Am. J. Energ. Res.*, **2**: pp.74–80.

Demirbas, A. (2005). Biodiesel production from vegetable oils by supercritical methanol. *J. Sci. Ind. Res.*, **64**:858–865.

Demirbas, A. (2009). Progress and recent trends in biodiesel fuels. *Energ. Convers. Manage.*, **50**: 14–34.

Heywood, J.B. (1988). *Internal Combustion Engine Fundamentals*. McGraw-Hill, New York

Iqbal, M.A., Varman, M., Hassan, M.H., Kalam, M.A., Hossain, S. & Sayeed, I. (2015). Tailoring fuel properties using jatropha, palm and coconut biodiesel to improve CI engine performance and

emission characteristics. *J. Cleaner Prod.*, **101**: 262–270.
Juoperi, K. (2008). Alternative fuels for medium-speed diesel engines. *WÄRTSILÄ Tech. J.*, **1**: 24–28.
Knothe, G., Gerpen, J.H. Van & Krahl, J. (2005). *The Biodiesel Handbook*. AOCS Press, Champaign,, Illinois.
Kumar, N. & Chauhan, S.R. (2013). Performance and emission characteristics of biodiesel from different origins: A review. *Renew. Sustain. Energ. Rev.*, **21**: pp.633–658.
Lin, C.-Y. (2014). Blending biodiesel in fishing boat fuels for improved fuel characteristics. *Front. Energ. Res.*, **2**: pp.2–6.
López, I., Pinzi, S., Leiva-Candia, D., Dorado, M.P. (2015). Multiple response optimizations to reduce exhaust emissions and fuel consumption of a diesel engine fuelled with olive pomace oil methyl ester / diesel fuel blends. *Energ.*, In press.
Malaysian Palm Oil Board (2016). *Overview of the Malaysian Oil Palm Industry 2015*, Kuala Lumpur.
Mekhilef, S., Siga, S. & Saidur, R. (2011). A review on palm oil biodiesel as a source of renewable fuel. *Renew. Sustain. Energ. Rev.*, **15**:1937–1949.
Ministry of Plantation Industries and Commodities Malaysia, 2006. *The National Biofuel Policy*, Available online at at: http://www.mpob.gov.my (Last access date: 5 September 2016).
Monirul, I.M., Masjuki, H.H., Kalam, M.A., Mosarof, M.H., Zulkifli, N.W.M., Teoh, Y.H. & How, H.G. (2016). Assessment of performance , emission and combustion characteristics of palm , jatropha and Calophyllum inophyllum biodiesel blends. *Fuel*, **181**: 985-995.
Murillo, S., Míguez, J.L., Porteiro, J., Granada, E. & Morán, J.C. (2007). Performance and exhaust emissions in the use of biodiesel in outboard diesel engines. *Fuel*, **86**:1765–1771.
Öztürk, E. (2015). Performance , emissions , combustion and injection characteristics of a diesel engine fuelled with canola oil – hazelnut soapstock biodiesel mixture. *Fuel Process. Tech.*, **129**:, 183–191.
Palash, S.M. Kalam, M.A., Masjuki, H.H., Masum, B.M., Rizwanul Fattah, I.M. & Mofijur, M. (2013). Impacts of biodiesel combustion on NOx emissions and their reduction approaches. *Renew. Sustain. Energ. Rev.*, **23**: 473–490.
Palocz-Andresen, M. (2013). Decreasing fuel consumption and exhaust gas Emissions in transportation. In *Marine Diesel Engines Marine*. Springer-Verlag Berlin Heidelberg, pp. 159–172.
Rakopoulos, D.C., Rakopoulos, C.D. & Giakoumis, E.G. (2015). Impact of properties of vegetable oil, bio-diesel, ethanol and n -butanol on the combustion and emissions of turbocharged HDDI diesel engine operating under steady and transient conditions. *Fuel*, **156**: 1–19.
Rashed, M.M. Kalam, M.A., Masjuki, H.H., Mofijur, M., Rasul, M.G. & Zulkifli, N.W.M. (2016). Performance and emission characteristics of a diesel engine fueled with palm, jatropha, and moringa oil methyl ester. *Ind. Crops Prod.*, **79**: 70–76.
Rizwanul Fattah, I.M. et al., 2014. Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends. *Energ. Convers.Manage.*, **79**: 265–272.
Rizwanul Fattah, I.M., Masjuki, H.H., Kalam, M.A., Mofijur, M. & Abedin, M.J. (2013). Impact of various biodiesel fuels obtained from edible and non-edible oils on engine exhaust gas and noise emissions. *Renew. Sustain. Energ. Rev.*, **18**: 552–567.
Roskilly, A.P., Nanda, S.K., Wang, Y.D. & Chirkowski, J. (2008). The performance and the gaseous emissions of two small marine craft diesel engines fuelled with biodiesel. *Appl. Thermal Eng.*, **28**: 872–880.
Roy, M.M., Wang, W. & Alawi, M. (2014). Performance and emissions of a diesel engine fueled by biodiesel–diesel, biodiesel–diesel-additive and kerosene–biodiesel blends. *Energ. Convers. Manage.*, **84**: 164–173.
Senthilkumar, S., Sivakumar, G. & Manoharan, S. (2015). Investigation of palm methyl-ester bio-diesel with additive on performance and emission characteristics of a diesel engine under 8-mode testing cycle. *Alexandria Eng. J.*, **54**:423–428.
Shojaeefard, M.H., Etghani, M.M., Akbari, M., Khalkhali, A. & Ghobadian, B. (2012). Artificial neural networks based prediction of performance and exhaust emissions in direct injection engine using castor oil biodiesel-diesel blends. *J. Renew. Sustain. Energ.*, **4**: 063130.

Wan Nor Maawa, W.G. Mamat, R., Masjuki, H.H. & Najafi, G. (2015). Effects of biodiesel from different feedstocks on engine performance and emissions: A review. *Renew. Sustain. Energ. Rev.*, **51**: 585–602.

Xue, J., Grift, T.E. & Hansen, A.C. (2011). Effect of biodiesel on engine performances and emissions. *Renew. Sustain. Energ. Rev.*, **15**:1098–1116.

Yasin, M.H.M., Paruka, P., Mamat, R., Yusop, A.F., Najafi, G. & Alias, A. (2015). Effect of low proportion palm biodiesel blend on performance, combustion and emission characteristics of a diesel engine. *Energ. Procedia*, **75**: 92–98.