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Effect of Al_2O_3 and SiO_2 Metal Oxide Nanoparticles Blended with POME on Combustion, Performance and Emissions Characteristics of a Diesel Engine

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ABSTRACT

Evaluation of combustion characteristic, engine performances and exhaust emissions of nanoparticles blended in palm oil methyl ester (POME) was conducted in this experiment using a single-cylinder diesel engine. Nanoparticles used was aluminium oxide (Al_2O_3) and silicon dioxide (SiO_2) with a portion of 50 ppm and 100 ppm. SiO_2 and Al_2O_3 were blended in POME and labelled as PS50, PS100 and PA50, PA100, respectively. The data results for PS and PA fuel were compared to POME test fuel. Single cylinder diesel engine YANMAR TF120M attached with DEWESoft data acquisition module (DAQ) model SIRIUSi-HS was used in this experiment. Various engine loads of zero, 7 N.m, 14 Nm, 21 N.m and 28 N.m at a constant engine speed of 1800 rpm were applied during engine testing. Results for each fuel were obtained by calculating the average three times repetition of engine testing. Findings show that the highest maximum pressure of nanoparticles fuel increase by 16.3% compared to POME test fuel. Other than that, the engine peak torque and engine power show a significant increase by 43% and 44%, respectively, recorded during the PS50 fuel test. Meanwhile, emissions of nanoparticles fuel show a large decrease by 10% of oxide of nitrogen (NO_x), 6.3% reduction of carbon dioxide (CO_2) and a slight decrease of 0.02% on carbon monoxide (CO). Addition of nanoparticles in biodiesel show positive improvements when used in diesel engines and further details were discussed.

Keywords: Nanoparticles; Al_2O_3; SiO_2; diesel; combustion.

INTRODUCTION

Pollution by diesel engine is a common matter in the automotive industry. It is due to the burning material of that engines that emits exhaust gas that was harmful to the environment. With the increase of world population, the pattern of environment pollution expected to increase. Manufacturer of the diesel-powered vehicle certainly will not fend off from considering to create less harmful emissions vehicle [1, 2]. Furthermore, the uncertainty of fuel prices and decrease of its reserves included by tight strict emission regulation, alternative fuel had become among the top in consideration to use other than that fossil fuels [3]. One of the methods to overcome these problems is to produce a biodiesel friendly vehicle [4]. However, the method of achieving the target will need unexpectedly much effort that can cause more cost to the manufacturer [5].On the contrary, a cost-effective method is to modify the biodiesel fuel so it can be compatible with the normal diesel engine. Biodiesel is known to have various biomass resources, biodegradable and environmental friendliness compare to fossil fuel due to its resources, biodiesel production becomes cost-competitive with these fossil fuels product [6-8]. Modifying the biodiesel does come with various strategies that can be performed and the final result expected is to get desired fuel properties than can run in a diesel engine with the engine maximum ability.

One of the methods of modifying biofuel is that by adding additive into it [9]. Even though there were various additives that can be used in biodiesel fuel, nanoparticles as an additive in biodiesel had shown several advantages when used in the diesel engine [10-12]. Addition of nanoparticles into biodiesel can aid in giving better properties of the biodiesel fuel. It can be seen when Fangsuwannarak et al. [13] stated that by adding titanium oxide (TiO_2) nanoparticles in palm oil biodiesel (POB), the kinematic viscosity of the POB reduced from 4.02 cSt to 3.68 cSt while the flashpoint and lower heating value of that POB increased by 1.3% and 2%, respectively. The authors suggested that by adding a small amount of TiO_2 nanoparticle into POB, the blended fuel was being thermally stable and the nanoparticle act as a catalyst to increase the combustion characteristics. Meanwhile, Caynak et al. [14] investigate the improvement of pomace oil mixed synthetic manganese additive had found that the density of the pomace oil decreased from 835 kg/m^3 to 828 kg/m^3. Lower viscosity, high cetane index and the lower heating value was the desired parameters for biodiesel fuel properties as it can improve combustion, shorten the ignition delay and safe to handle.

Kannan et al. [15] use ferric chloride ($FeCl_3$) blended in waste cooking palm oil biodiesel with the portion of 20 μmol/l found that brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) had improved 8.6% and 6.3%, respectively. Meanwhile, Durairaj et al. [16] investigate cerium oxide (CeO_2) nanoparticles blended with cottonseed and neem oil biodiesel fuel blends concluded that the oxygen in biodiesel facilitated in improved combustion and CeO_2 nanoparticles give advantage to the engine operate in lean mixture and support improve ignition delay and increase BTE. Meanwhile for Basha and Anand et. al. [17] that uses Jatropha biodiesel emulsion fuel blended with alumina nanoparticles concluded that the combustion and performance of diesel engine improved due to alumina nanoparticles benefited from the reduction of ignition delay. Aluminium based nanoparticles were the most used as an additive in diesel fuel and there were also researchers that use it on biodiesel. From the literature review, it can be seen that the addition of metal oxide nanoparticles into biodiesel fuel was giving positive results when tested in a diesel engine by shortening the ignition delay which improves engine combustion and increases BTE [18-20].

On the other hand, silicon-based nanoparticles were also showing good results in term of properties and engine performance to the diesel engine. This can be seen when Ozgur et al. [21] uses SiO_2 and MgO nanoparticles blended in rapeseed methyl ester. The authors found that brake power and torque of diesel engine improves significantly, while CO and NO_x emission decreased by 10.4% and 7.2%, respectively. Another research by Ozgur et al. [22] that use nine different nanoparticle additives namely aluminium oxide (Al2O3), magnesium oxide (MgO), titanium oxide (TiO2), zinc oxide (ZnO), silicon oxide (SiO2), iron oxide (Fe2O3), nickel oxide (NiO), nickel-iron oxide (NiFe2O4) and nickel-zinc iron oxide (Zn0.5Ni0.5Fe2O4) reported that the NO_x emission of diesel engine decreased by 8.3% on biodiesel+SiO_2 blends. Besides palm oil, there was also researcher that use Jatropha biodiesel blended with magnalium and cobalt oxide nanofluid and the researcher suggested that the cobalt oxide reduce the NO_x by 47% [23]. Reduction of harmful emission is achieved by complete combustion and high BTE that supported by high peak pressure and HRR [24-26].

Based on the literature, this study focusses on combustion, performance and exhaust emission of Al_2O_3 and SiO_2 blended in palm oil methyl ester (POME). Taking considerations that Al_2O_3 is broadly used in this research field, data collected by this study method can be used to compare with SiO_2 data results for further actions. Moreover, SiO_2 was chosen for this study due to the best of author knowledge, there were no researchers that study its effect on the diesel engine when blended in POME.

RESEARCH METHODOLOGY

Fuel Preparation Method

For this experiment, Al_2O_3 and SiO_2 with a size range between 20-30 nm were supplied by Sigma-Aldrich Corporation. Size of both nanoparticles was confirmed by dispersion analysis carried out using JOEL JSM-7800F Schottky field emission scanning electron microscope (FESEM) as shown in Figure 1(a) and 1(b). The nanoparticles were blended into POME with the portion of 50 mg and 100 mg by weight for each nanoparticle. An ultrasonic emulsifier model Hielscher ultrasonic GmbH UP400S was used to mix the nanoparticles into POME at 50% power and 0.7 seconds cycle for 30 minutes to obtain a well-blended mixture of nanoparticle-biodiesel fuel. The test fuel physio-chemical properties were carried out by following ASTM standard characterization where it attained ASTM D6751-08 and EN14212 standard. The test fuel was named as PS50 and PS100 for SiO_2 + POME blend while PA50 and PA100 for Al_2O_3 + POME blend. Finally, the fuel was placed in a test tube for stability test by observation for 14 days. For the first 7 days, there were no obvious changes to the test fuel. In the next 7 days, PA50 and PA100 test fuel show a slight change in colour where it turns lighter compared to POME. Results from the observation, there was no noticeable surface separation on test fuel.

(a) Al_2O_3 (b) SiO_2

Figure 1. FESEM micrographs of nanoparticles.

Test Engine and Instrument Setup

In this experiment, the engine used was a single-cylinder YANMAR TF120M water-cooled direct injection diesel engine. The engine is naturally aspirated air intake and the injection timing is at 17° before Top Dead Centre (bTDC). Detail specifications of the engine are shown in Table 1. Figure 2 shows the schematic diagram of the experiment setup, the eddy current dynamometer used from Focus Applied Technologies model BD-15kW with the maximum power of 15 kW mounted to the spherical bearing and was fitted directly to the test engine. An S-type load cell force sensor model Zemic H3-C3-500kg-3B was used to measure the brake torque of the diesel engine. On the other hand, to measure the fuel mass flow rate by recording the time required to consume a specific mass of the fuel was a digital weight scale from CAS (TCS- up to 6kg). A thermocouple logger, model PicoLog TC-08 USB was used to measure the exhaust gas temperature, fuel temperature, and the ambient air temperature. Data acquired by PicoLog was recorded in DasyLab Software where the data was then transferred into Excel Worksheet. Meanwhile, for combustion characteristic data, DEWESOFT software was used to record the data and equipped with data acquisition (DAQ) model SIRIUSi-HS. Crankshaft angle sensor was used to obtain the crankshaft position, which determines the cylinder gas pressure as the function of the crank angle. The cylinder pressure was measured by an Optrand optic-fibre pressure sensor model Auto-PSI C82294-Q. Meanwhile, engine speed was measured using the Hall Effect proximity sensor model AOTORO SC12-20k.

Table 1. Engine specifications.

Properties	Value
Engine type	YANMAR TF120M
Number of cylinders	1
Bore x Stroke	92 x 96 mm
Displacement	0.638 L
Compression ratio	17.7
Injection timing	17° bTDC
Continuous output	10.5 HP at 2400 rpm
Rated output	12 HP at 2400 rpm
Cooling system	Water-cooled

Engine Test Cycle and Procedure

During this experiment, the result of all test fuel was recorded at constant 1800 rpm and various engine loads of zero, 7 N.m, 14 N.m, 21 N.m and 28 N.m. Each data record for all engine loads was repeated three times and an average result was calculated and used as final result data. The experiment started by fueling the engine with diesel fuel for 15 minutes to warm it up to operating temperature before it was tested with the test fuel to secure the data. The engine was run for 5 minutes to ensure all data value gained is at a steady pace before it was recorded.

Uncertainty Analysis

During the experiment, uncertainty contributed by several factors such as setup, environment, method of measuring and type of instruments [27]. During this experiment, the measurement of engine performance and emission were recorded 5 minutes after the engine was set at the desired condition to ensure no changes in parameters. Table 2 shows the measuring range and accuracy of measured parameters during experiments. For computed parameters such as BSFC, BTE and brake power, the uncertainties were calculated based on uncertainties propagation of relevant measurable parameters by using Eq. (1) and (2). Total uncertainty for calculated and measured parameters was sum up based on the root mean square of experimental data uncertainty and instrumental uncertainty [28, 29]. The average of total uncertainties for each parameter presented in Table 3. The general formula for uncertainty propagation was as follows:

$$Y = X_1 \times X_2 \times X_3 \ldots X_n \tag{1}$$

$$[\Delta Y]^2 = \sum_{i=1}^{n} \left[\frac{\delta Y}{\delta X_i} \times \Delta X \right]^2 \tag{2}$$

Where, Y: parameter, ΔY: uncertainty of parameter, $X_1, X_2, X_3, \ldots X_n$: variables of Y and; ΔX_1, ΔX_2, $\Delta X_3, \ldots \Delta X$: accuracy or uncertainty of variables.

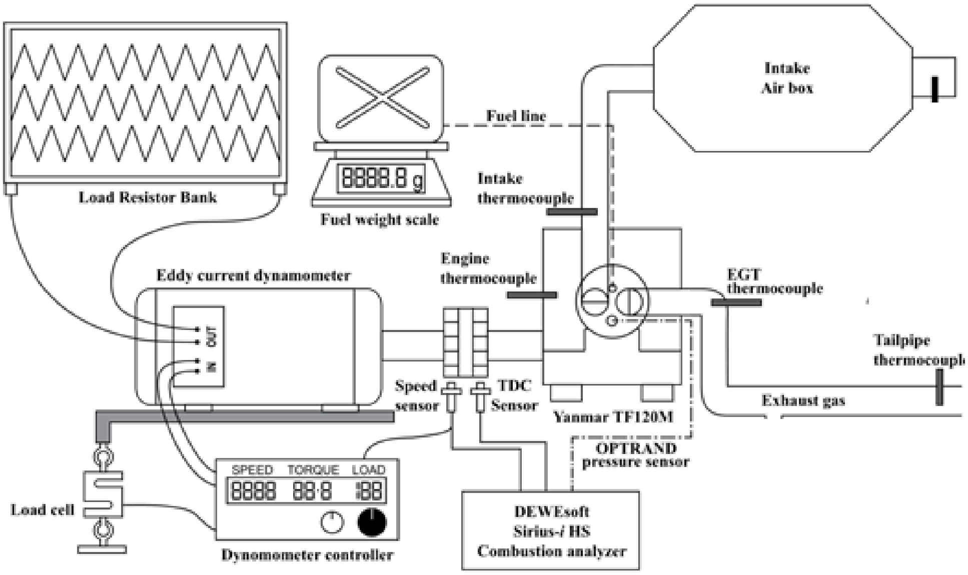

Figure 2. Schematic diagram of the experimental setup.

Table 2 Measurement parameters.

Measured parameter	Measuring range	Accuracy
Engine speed	0–2500 rpm	±50 rpm
Fuel mass	0–6 kg	1 g
Exhaust gas temperature	30–1000 °C	±5 °C
CO	0–10 vol%	±0.06 vol%
CO_2	0–16 vol%	±0.5 vol%
NO_x	0–5000 ppm	± 5% reading
Engine torque	0–40 Nm	±0.18 Nm

RESULTS AND DISCUSSION

Fuel Properties

Properties of test fuel presented in Table 4 shows that the addition of nanoparticles to POME has no noticeable effect on the density of the test fuel. The calorific value of 50 ppm dosage nanoparticles shows an increase while for 100 ppm dosage show a decrease and expected to affect BTE and BSFC during engine testing.

Table 3 Average of total uncertainty.

Parameter	Variable or unit of parameter	Average total uncertainty
CO	vol%	±0.06 vol%
CO_2	vol%	±1.30 vol%
NO_x	ppm	±7.11%
EGT	°C	±10.36%
Torque	Nm	± 6.56%
Brake power	Engine speed, torque	± 8.01%
BSFC	Brake power, fuel consumption	±11.02%
BTE	Brake power, fuel consumption, calorific value	±16.12%

Table 4. Properties results of test fuel.

Properties	Unit	PS50	PA50	PS100	PA100	POME
Density	kg/m^3	873	874	874	876	872
Calorific value	MJ/kg	44.15	44.71	43.12	43.46	43.63
Cetane Number		55.60	54.24	53.03	49.89	48.15

In-Cylinder Pressure

In-cylinder pressure versus crank angle (CA) at 28 N.m engine load shown in Figure 3. Using this engine setup, the cylinder pressure increases with the increase of engine load for all test fuel. The data also shows that the highest maximum pressure was recorded by PS50 test fuel at 74.5 Bar during 28 N.m engine load. Meanwhile, for other test fuel, maximum pressure recorded was 73.9 Bar and 63.9 Bar for PA50 and POME where the data was also gained at 28 N.m engine load operation. Other than in-cylinder pressure, from the graph, it also shows that the ignition duration for each test fuel. POME fuel ignition started at -5 CA and ended at 7 CA while for both PA50 and PS50 fuel the ignition started after -5 CA and ended before 5 CA.

Meanwhile, for PA100 and PS100 test fuel, their in-cylinder pressure is as shown in Figure 3. The maximum pressure for PA100 recorded was 73.6 bar and 75.3 bar were recorded for PS100 fuel. In-cylinder pressure during all five different loads applied to the engine shows that nanoparticle blended POME fuels increase the combustion pressure compared to POME fuel. This behaviour was due to the shortening of ignition delay of nanoparticles fuels that contribute to better combustion when the piston was closer to TDC. Nanoparticles blended fuels help to increase the surface area to volume ratio that provides contact to the surface area which helps in better oxidisation where it can double the energy during fuel combustion or when molecule explode [30, 31].

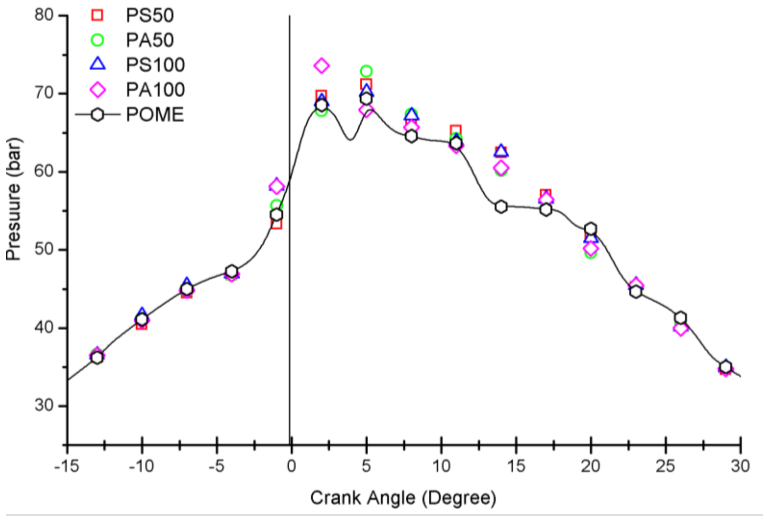

Figure 3. Pressure variation during 28 N.m engine load.

Heat Release Rate

Variations of heat release rate (HRR) of test fuels presented in Figure 4. The highest HRR was produced by PS100 test fuel during 21 N.m engine load applied with 6015.40 J/CA which is 21.7% increase compared to POME test fuel that gives maximum HRR at 49400.77 J/CA at same engine load. Meanwhile, other test fuels also show an increase of HRR when compared to POME fuels with the increment of 17.74%, 15.45%, and 12.2% for PA50, PA100 and PS50 test fuel.

The reason behind this behaviour was due to the fast evaporation rate, enhanced ignition properties and improved surface area to volume ratio that resulting in a shortened ignition delay and improved combustion process [32]. Nanoparticles are expected to increase the HRR due to the shorter ignition period during combustion that caused the HRR to maximize during this period. The shorter the duration of ignition delay the peak of HRR will increase [33, 34].

Engine Performance

Figure 5 shows variation of torque produced by test fuels at all engine load. Graph generated from the data clearly shows that nanoparticle test fuels emits better torque compared to POME test fuel at all five load variations. Highest torque was produced by PS50 test fuel with the increase of 43.95% compared to POME test fuel at 7 N.m engine load. Torque from PS50 fuel also give significant increment at zero engine load, 14N.m engine load, 21 N.m engine load and 28 N.m engine where the increment was 19.27%, 12.6%, 18.74% and 6.54%. PS100 test fuel also shows promising increase of engine torque where data shows the increase of 17.94%, 28.8%, 12.6%, 6.97% and 3.45% during zero load, 7 N.m, 14 N.m, 21 N.m and 28 N.m load applied applied to the engine. The amount of torque produced is parallel to the combustion pressure during combustion where the increase in combustion pressure will increase the amount of torque produced [35].

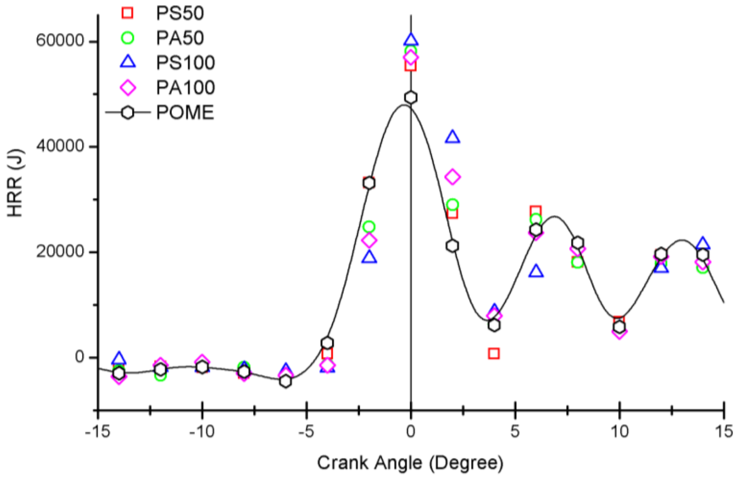

Figure 4. HRR of test fuel during 21 N.m engine load setup.

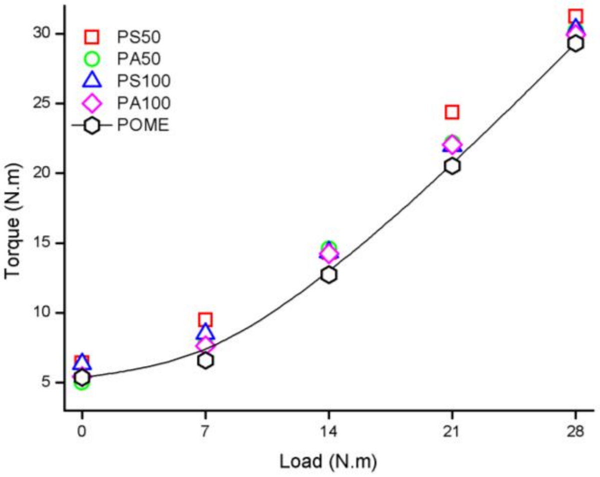

Figure 5. Results of engine torque variations.

Meanwhile, engine power variations versus engine load for this study was presented in Figure 6. Parallel to engine torque, when fueled with PS50 fuel blend shows an increase of engine power with 19%, 43%, 0.5%, 18.7% and 6.5% at zero load, 7 N.m, 14 N.m, 21 N.m and 28 N.m engine load. Another significant increase was also by PS100 test fuel with the highest power emits was during 7 N.m engine by 29% by percentage compared to POME test fuel. The increment of power with the increment of engine speed and load added to the engine was common in the usage of nanoparticles or metal as an additive in test fuel [36].

Other engine performance that were included in this study was the BTE produced by the engine when fueled with these test fuel. Figure 7 shows data collected from the experiment for BTE variations versus engine load. Engine BTE increase with the increment of engine load applied and it can be seen that percentage of BTE for PS50 from data collected shows a slight increase compared to another test fuel. The increase of BTE for PS50 fuel was 0.02%, 0.06%, 0.01%, 0.03% and 0.001% for zero load, 7 N.m, 14 N.m, 21 N.m and 28 N.m engine load operations. The positive result from the nanoparticle blended POME fuel is due to high surface area and reactive surfaces that contributed to higher chemical reactivity to act as a potential catalyst [37].

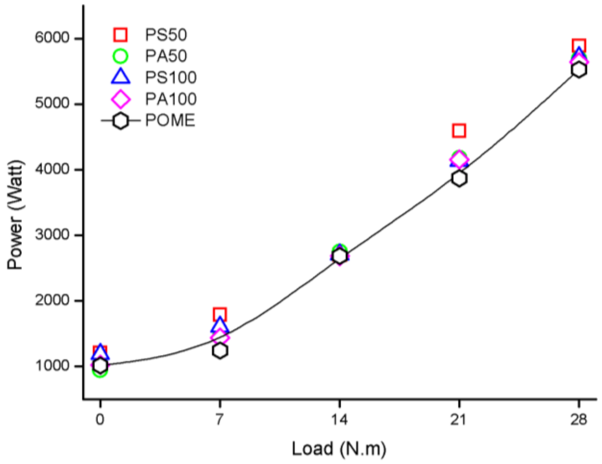

Figure 6 Engine power recorded from all test fuel

BSFC for this study is presented in Figure 8 below. BSFC results for PS50 test fuel shows an increase at 28 N.m engine load with 8.9% compared to POME test fuel. Meanwhile for zero load, 7 N.m, 14 N.m, 21 N.m and 28 N.m engine load decrease with 13%, 0.9%, 4% and 9.1% significantly. PS100 on the other hand shows a slight decrease of BSFC at 21 N.m load with 0.05% while at zero load, 7 N.m, 14 N.m and 28 N.m engine it BSFC increase by 6.2%, 13.2%, 2% and 5%. PA 50 fuel blend, however, shows an increase in BSFC at 14 N.m and 21 N.m engine load by 4.9% and 0.8% when compared to POME test fuel and shows a decrease at zero engine load, 7 N.m and 28 N.m engine load by 8.1%, 13.6% and 5.4%. Increase of BSFC by nanoparticles fuel was due to the decrease of calorific value that effect engine to consume more fuel. Other than that, when blended together in POME, nanoparticles reacted due to the higher surface area to volume ratio of the nanoparticles and improved the fuel-air mixing that supports by the density of the fuel during injection [38].

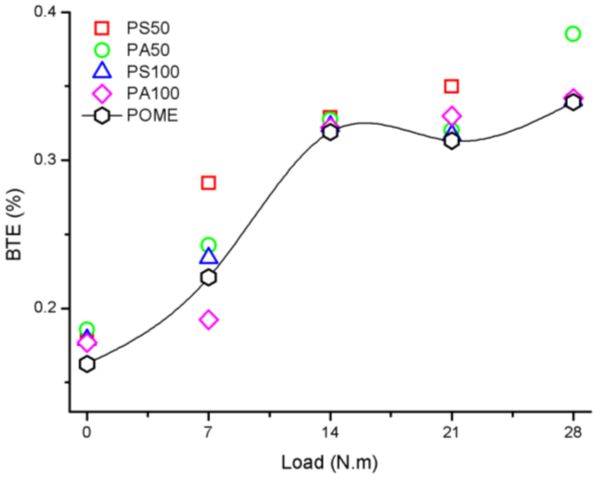

Figure 7 Percentage of BTE versus engine load setup.

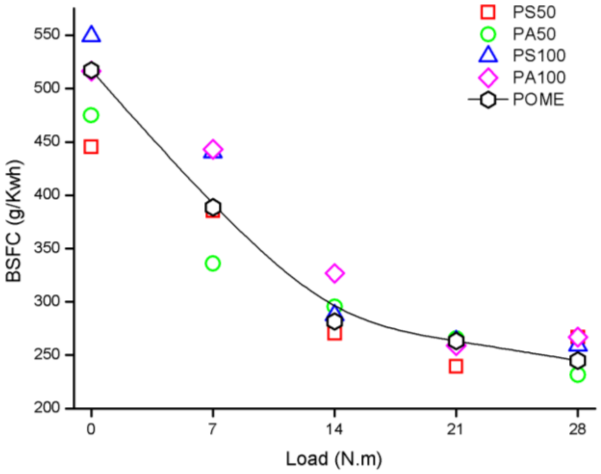

Figure 8. Results of fuel consumption in g/Kwh

Exhaust Gas Emission

Figure 9 shows the carbon monoxide (CO) emission results from the experiment. Nanoparticles fuel blends show a reduction of CO emission compared to POME test fuel. The reduction of CO is due to the shorter ignition delay and enhanced combustion characteristic of test fuel in the engine. The significant difference of CO reduction can be seen during 28 N.m engine load where PS50 and PA50 CO readings come to 0.022% and 0.032% while POME test fuel CO readings exceed 0.04%. Other than that, PS100 and PA100 reading were slightly higher where both test fuel show 0.04% CO reading. Nanoparticles act as an oxygen donating catalyst for the oxidation of CO which can also contribute to lower NO_x [39].

Other than CO emissions, carbon dioxide (CO_2) exhaust emissions were also monitored during this study experiment. In Figure 10 it can be seen that CO_2 emission of nanoparticles fuel show reduction at 21 N.m engine load operation where the reading recorded for PS50, PS100, PA50 and PA100 was 6.3%, 6.36%, 6.26% and 6.46% which is lower than POME test fuel with recorded data of 6.8%. Meanwhile, on 28 N.m engine load operation, lowest reduction recorded for CO_2 was by PS50 and PS100 test fuel with 8.83% and 8.86% compared to POME test fuel with 9.25% reading where CO emission reduction was contributed by the improvement of the evaporation rate of fuel droplets [40].

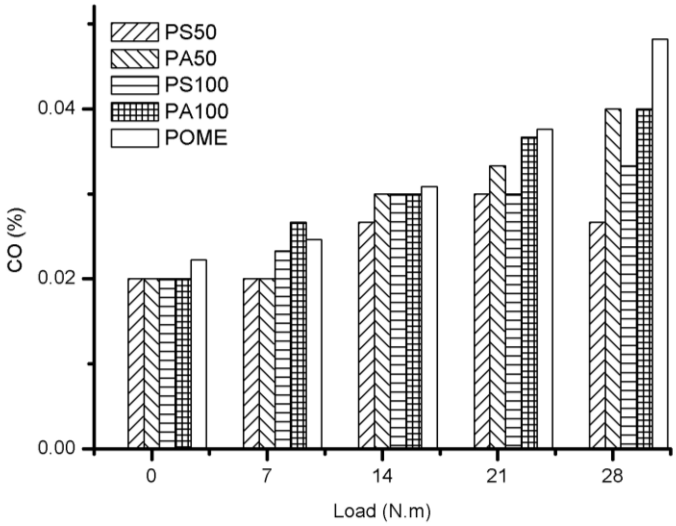

Figure 9. Percentage of CO emission produced.

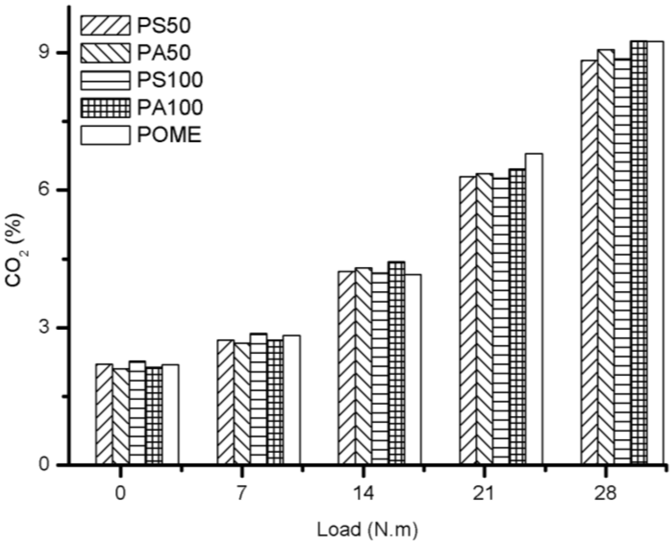

Figure 10 CO_2 emissions of test fuel recorded.

Oxides of nitrogen (NO_x) is a gas that is considered dangerous due to its ability and further reaction that can cause acid rain. NO_x is producing from nitrogen and oxygen from combustions reactions at high temperature. Considering the hazardous effect that can be obtained from NO_x where it's a reduction from the combustion is favourable. Figure 11 presented is a variation of NO_x measured in ppm. Nanoparticles test fuel shows a slight reduction of NO_x for all engine load operations compared to POME test fuel. Significant NO_x reduction was by PA50 test fuel during all engine load operation where the data recorded was 10.2%, 8.9%, 6.7%, 9.4% and 7% reduce when compared to POME test fuel at zero engine load, 7 N.m, 14 N.m, 21 N.m and 28 N.m. Meanwhile, for PS50 test fuel, highest percentage reduction was during 14 N.m engine load operations which is 4.48% and for PA100 and PS100 test fuel, the highest reduction of NO_x was 9.1% and 3.8%. Higher HRR contributes to the reduction of NO_x for nanoparticles fuel blend which it helps the engine to process complete combustion [41].

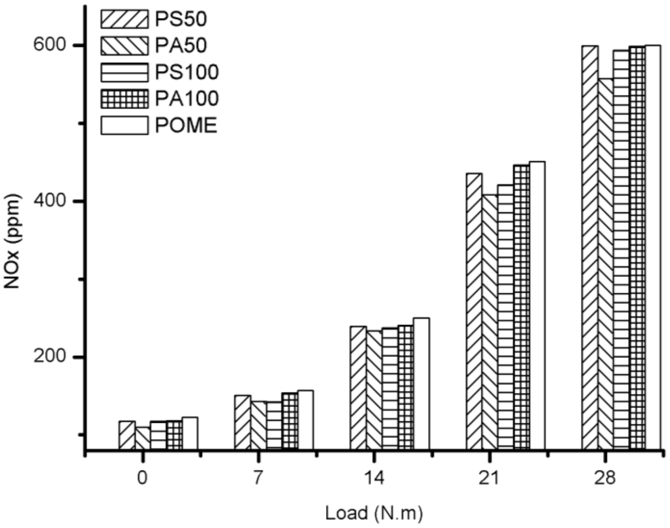

Figure 11. NO_X recorded in the unit of ppm.

CONCLUSION

Results obtained in this study decided that biodiesel-nanoparticles blends show positive improvement when used in a diesel engine. Based on the presented results, the following points emerged to attention:

i. Nanoparticles resulted in no noticeable effect on density when blended in POME but aid in the increase of calorific value when blended with the portion of 50 ppm on both nanoparticles
ii. PS and PA fuel shows an increase of peak pressure by 16.5% and 15.3% during 28 N.m engine load and improve in HRR by 21.7% at 21 N.m engine load.
iii. Engine power and torque of nanoparticles-biodiesel blend show the total average of improvement by 15% as engine load increase the torque and power also increase.
iv. BTE shows a slight improvement for all test fuel compared to POME, while only BSFC of PS50 and PA50 shows an improvement by 15% reduction in fuel consumption.
v. Exhaust emission of PS and PA test fuel shows improvement on CO, CO_2 and NO_x, where the average reduction in total was 0.4%, 8% and 9.2%, respectively.

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