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Effect of Thermal Barrier Coating on the Performance and Emissions of Diesel Engine Operated with Conventional Diesel and Palm Oil Biodiesel

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Abstract: In this study, the performance and emission of a thermal barrier coating (TBC) engine which applied palm oil biodiesel and diesel as a fuel were evaluated. TBC was prepared by using a series of mixture consisting different blend ratio of yttria stabilized zirconia ($Y_2O_3{\cdot}ZrO_2$) and aluminum oxide-silicon oxide ($Al_2O_3{\cdot}SiO_2$) via plasma spray coating technique. The experimental results showed that mixture of TBC with 60% $Y_2O_3{\cdot}ZrO_2$ + 40% $Al_2O_3{\cdot}SiO_2$ had an excellent nitrogen oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbon (HC) reductions compared to other blend-coated pistons. The finding also indicated that coating mixture 50% $Y_2O_3{\cdot}ZrO_2$ + 50% $Al_2O_3{\cdot}SiO_2$ had the highest brake thermal efficiency (BTE) and lowest of brake specific fuel consumption (BSFC) compared to all mixture coating. Reductions of HC and CO emissions were also recorded for 60% $Y_2O_3{\cdot}ZrO_2$ + 40% $Al_2O_3{\cdot}SiO_2$ and 50% $Y_2O_3{\cdot}ZrO_2$ + 50% $Al_2O_3{\cdot}SiO_2$ coatings. These encouraging findings had further proven the significance of TBC in enhancing the engine performance and emission reductions operated with different types of fuel.

Keywords: TBC; palm oil biodiesel; diesel engine

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1. Introduction

Exploration on the energy-efficient engine has always driven engineers as the total consumptions of petroleum-based fuel such as diesel was increased proportionally with the demands from the power generation, industrial and transportation areas [1]. Therefore, introduction of TBC into the engine design is necessary to overcome efficiency problems as this coating technology was proven significantly to increase power and decrease specific fuel consumption [2]. Besides that, other positive advantages from TBC application were reduce heat loss leading to thermal efficiency, less pollution, and increased durability of engine components [3].

Depletion of world petroleum-based fuel reserve, uncertainty in fuel price, increasing emission of greenhouse gases have raised the interest to research alternative and sustainable energy resources. Biodiesel, which is non-toxic and a renewable energy resource was introduced as an alternative solution for diesel [4]. This environmentally friendly energy resource results in less emission of greenhouse gases, unburned HC and polycyclic aromatic compounds [5]. However, application of biodiesel in unmodified the internal combustion diesel engine significantly declined the performance of the engine and its combustion characteristics, which might be caused by the physicochemical properties of the biodiesel [6,7]. Thus, various aspects of engine modification have been explored in order to overcome this drawback and the TBC seems a positive solution [8,9].

Most commonly used TBC such as Yttria-partially-stabilized zirconia (YPSZ) [10], partially stabilized zirconium (PSZ), Yttria stabilized zirconia (YSZ) [11], magnesia-stabilized zirconia (MSZ) [2], and aluminum oxide Al_2O_3 [12] is used to coat blades in gas turbine engines for better thermal efficiency. Some of these ceramic coating had been tested in diesel engine with Pongamia oil, cotton seed oil [13], crude Jathropha oil with carbureted oil, diesel oil with significant improvement in terms of thermal efficiency. PEO ($Al_2O_3{\cdot}ZrO_2{\cdot}SiO_2$), triphase composite ceramic coating, $Al_2O_3{\cdot}ZrO_2$ together with a small amount of SiO_2 (SiASZ) has good thermal shock resistance [14]. However, $Al_2O_3{\cdot}SiO_2$ coating was not tested with palm biodiesel and not evaluated in engine performances and emission analysis. This coating material is believed can improve furthermore on thermal efficiency and BSFC as it possesses high thermal insulation capability and with addition of SiO_2 might improvise NO value.

There has been a gap in the research for TBC whereby the NO emissions were higher than uncoated piston. Theoretically, NO values will increase with the increase of heat. Hence, for this experimental, the coating is done on piston crown only and it is believed that the NO emission will reduce since the heat is capsuled partially. Thus, in this work, three objectives are completed, (1) identify optimum blend ratio of TBC between $Y_2O_3{\cdot}ZrO_2$ and $Al_2O_3{\cdot}SiO_2$ (2) analyze engine performance and emission for coated piston, and (3) comparison between standard diesel and biodiesel as a fuel for coated engine.

2. Materials and Methods

Figure 1 shows the schematic view of the experimental setup which includes a single cylinder, four strokes, direct injection diesel engine. The detail for the test engine used was Kubota RT 125 (Kubota, Osaka, Japan) as mentioned in Table 1. Figure 2 indicates the experimental setup including an eddy current dynamometer (KAMA, Fujian, China) to alter or tune the engine load. This setup is equipped with data acquisition system to collect data and analyze the performance of tested fuels and coating pistons.

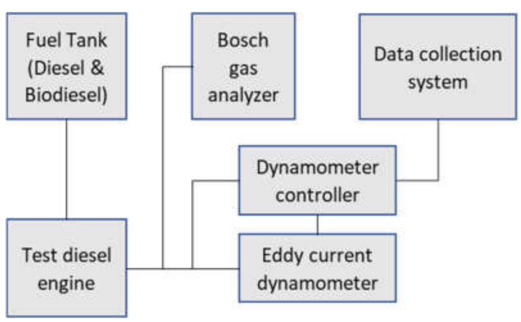

Figure 1. Schematic diagram for the experimental setup.

Table 1. Engine specification.

Model	RT125DI-ES
Type	Water cooled 4 stroke horizontal diesel engine
Cylinder No	1
Bore x Stroke	94 mm × 96 mm
Displacement	666 cc
Max. Output	9.2 kW/2400 rpm
Compression Ratio	18:1
Max. Torque	4.7 kgf-m/1600 rpm
Combustion System	Direct injection
Battery	12 V, 30 Amp
Dry Weight	116 kg

Figure 2. Kubota RT-125 diesel engine experimental setup.

The engine load absorber (KAMA, Fujian, China) is based on the 7.5 kW A.C. synchronous dynamometer. It is used to provide loading to the engine and to maintain the engine speed. The fuel flow rate was measured with a DOM-A05H flow meter connected to a ZOD-Z3 flow rate totalizer (Kobold, Nordring, Germany). BOSCH BEA 150 is used to analyze the exhaust emissions from the engine such as CO, CO_2, HC, and NO as shown in Figure 3. The measurement range and accuracy of instrument used are given in Table 2. Smoke analyzer (BOSCH, Gerlingen, Germany) was used to collect smoke samples from the engine, through smoke sampling sensor to measure smoke opacity.

Figure 3. Photo of gas analyzer BOSCH BEA-150.

Table 2. Specification of the gas exhaust component.

Description	Value	
Exhaust Component	**Measurement Range**	**Resolution**
CO	0.000–10.00 vol.%	0.001 vol.%
CO_2	0.00–18.00 vol.%	0.01 vol.%
HC	0–9999 ppm vol.	1 ppm vol.
NO	0–5000 ppm vol.	<=1 ppm vol.

The test was conducted with various speeds setting at full loaded engine operation condition. Full load engine is achieved at 1000 rpm. Since the engine was highly vibrated during full load, for the safety reason, speed of the engine was reduced to 1200 rpm instead of 1000 rpm for this experimental work. The engine was throttled to maximum and then locked. The speed of the engine was gradually reduced by 200 rpm decrement from 2400 rpm to 1200 rpm. As the speed decreases, the dynamometer was increased with the load of the engine to achieve the desired speed. The same step was repeated for each piston and fuel test. The test was repeated at an average of three times and the average value was reported in this paper. The tests were repeated three times to ensure consistency of the value and to reduce measurement errors. The data were collected for speed from 1200, 1400, 1600, 1800, 2000, 2200, and 2400. All the data captured, were translated into a graph for analysis. Every time before taking readings, the engine was run at steady condition for 5 to 7 min for all the test fuel and test piston. Measurement was taken for fuel consumption, torque, power, oxygen, NO, HC, CO, and CO_2. The required engine speed was adjusted using eddy current dynamometer. All the testing and date collection were done by using a controller and saved in the computer. Exhaust emission test were measured out with the smoke analyzer (BOSCH, Gerlingen, Germany). This device also has special features equipped with a NO sensor and able to measure the smoke opacity with the help of additional probe linked to the opacimeter unit. Gravimetric type fuel consumption meter was used to measure the fuel flow rate.

For this experiment, five (5) types of pistons have been prepared as mentioned in Table 3 in comparison to uncoated piston. The piston crowns were coated with blend between coating powder of $Y_2O_3{\cdot}ZrO_2$ coating and $Al_2O_3{\cdot}SiO_2$ coating. The TBC were built on the piston crown by using plasma spray technique. NiCrAl was used as base coat (BC) to bond the TBC with the surface of crown piston. The configuration of blended TBC between $Y_2O_3{\cdot}ZrO_2$ and $Al_2O_3{\cdot}SiO_2$ coating built on piston crown were presented in Figure 4. The piston crown mentioned were coated with the 100 µm NiCrAl as lining layer and the same piston was coated with 400 µm materials of TBC coating. Both $Y_2O_3{\cdot}ZrO_2$ and $Al_2O_3{\cdot}SiO_2$ were in powder form. By applying plasma spray, the abrasive powder is melted in ionized gas on the piston surface, resulting in the formation of coating layer on the piston crown. The plasma spray was equipped with powder feeder, gas supply, spray gun, power unit, controller, cooling unit, and holder. The ceramic coating materials of $Y_2O_3{\cdot}ZrO_2$ (purity 99.9%) and $Al_2O_3{\cdot}SiO_2$ (purity 99.9%) used in this experimental test were readily available. Prior to the application of coating, acetone was used to clean the surface of the piston and the process proceeded with grit blasting to increase its surface roughness in order to enhance the grip of the coating to the surface of the piston. In addition, the tested fuels, along with the local suppliers of the commercial diesel and B100 palm biodiesel are listed in Table 4.

Figure 4. Piston crown configuration with specific coating mixture.

Table 3. List of TBC mixture.

Coating Mixtures	Fuel	Acronym	Note
Non-Coated	Diesel	ND	Non-Coated Diesel
	B100 Palm	NB	Non-Coated Biodiesel
Coated 90% $Y_2O_3{\cdot}ZrO_2$ +	Diesel	90/10D	90/10 Diesel
10% $Al_2O_3{\cdot}SiO_2$	B100 Palm	90/10B	90/10 Biodiesel
Coated 80% $Y_2O_3{\cdot}ZrO_2$ +	Diesel	80/20D	80/20 Diesel
20% $Al_2O_3{\cdot}SiO_2$	B100 Palm	80/20B	80/20 Biodiesel
Coated 70% $Y_2O_3{\cdot}ZrO_2$ +	Diesel	70/30D	70/30 Diesel
30% $Al_2O_3{\cdot}SiO_2$	B100 Palm	70/30B	70/30 Biodiesel
Coated 60% $Y_2O_3{\cdot}ZrO_2$ +	Diesel	60/40D	60/40 Diesel
40% $Al_2O_3{\cdot}SiO_2$	B100 Palm	60/40B	60/40 Biodiesel
Coated 50% $Y_2O_3{\cdot}ZrO_2$ +	Diesel	50/50D	50/50 Diesel
50% $Al_2O_3{\cdot}SiO_2$	B100 Palm	50/50B	50/50 Biodiesel

Table 4. List of physical and chemical properties of biodiesel and diesel fuels.

Properties	Diesel	Diesel B100 Palm
Density at 18 °C (g/m^3)	0.8210	0.8833
Kinematic viscosity at 35 °C (mm^2/s)	2.5	4.30
Calorific value (kJ/kg)	42,950	38,108
Cetane number	46	52
Flash point (°C)	50	140

3. Results

The effects of TBC with various blend ratios of $Y_2O_3{\cdot}ZrO_2$ and $Al_2O_3{\cdot}SiO_2$ on the emission control and engine performance using conventional diesel and biodiesel are further discussed in this section.

3.1. Engine Emissions

In this section, the engine emissions such as HC, NO, CO, and CO_2 were evaluated in terms of different TBC ratio of $Y_2O_3{\cdot}ZrO_2$ and $Al_2O_3{\cdot}SiO_2$. Non-coated pistons registered lowest amount release of HC compared to the coated pistons. With the increase of speed, 50/50B and 60/40B performed as greater as NB. HC yielded slightly higher with the increase of 10% (70/30) of coating against a baseline coat of 60/40. HC yielded slightly lower with the decrement of 10% (50/50) of coating against a baseline coat of 60/40.

At maximum load, for HC emission (Figure 5) against variable speed for Kubota Diesel Engine for all coated pistons tested under diesel, the 70/30D with 112 ppm indicates lowest amount release of HC, followed by 60/40D;114 ppm, 80/20D; 141 ppm, 50/50D; 149 ppm. In case of biodiesel, the 60/40B with 78 ppm indicates lowest amount release of HC, followed by 50/50B; 81 ppm, 70/30B; 81 ppm, 80/20B; 107 ppm. 60/40D and 60/40B maintain good stability and release lowest amount of HC for both diesel and biodiesel test fuel compared to other coating mixture. As an assumption, biodiesel releases lower amount of

HC compared to diesel as biodiesel fuel contained more oxygen molecule in achieving better combustion [13,15–17]. The decreasing emission of HC on the coated engine was related to the increasing of heat on the combustion chamber [13].

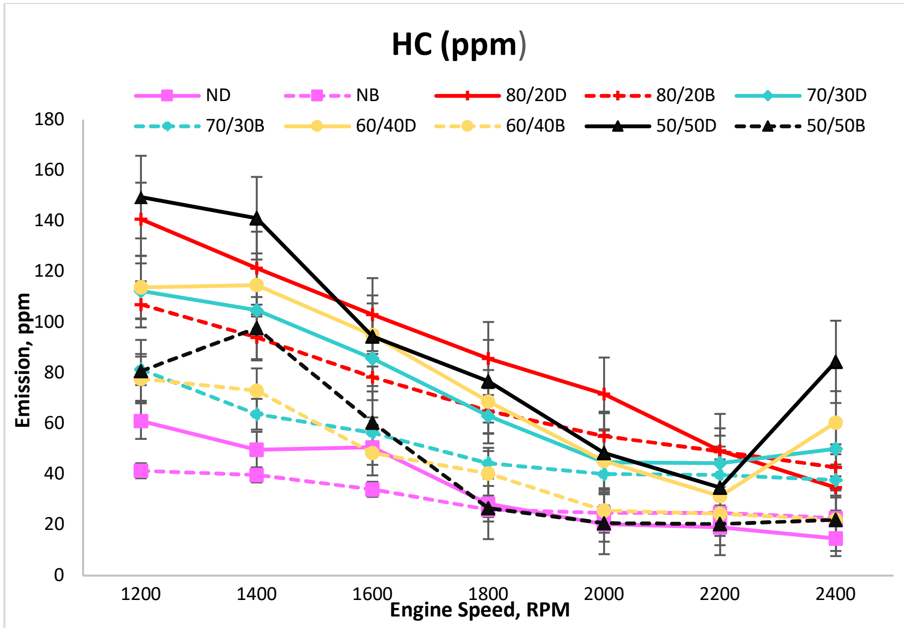

Figure 5. HC emission.

On the other hand, Figure 6 exhibits the effect of NO emission against variable speeds for coated and uncoated pistons for both diesel and biodiesel fuels. The NO reading was found to be better due to an increase of combustion duration with the introduction of trapezoidal piston. Trapezoidal pistons lengthen the duration of combustion with the swirl effect and ensure better mixture of air and fuel. Figure 6 indicated that all the coated pistons registered lowest amount of NO release compared to non-coated pistons. NO yielded lower with the 10% (70/30) incremental of coating against a baseline coat of 60/40. NO yielded slightly higher with the decrement of 10% (50/50) of coating against a baseline coat of 60/40. Figure 6 also indicated NO emission against variable speed for all coated pistons tested under diesel, the 60/40D released of lowest amount NO, about 240 ppm, followed by 70/30D;243 ppm, 80/20D; 363 ppm, 50/50D; 442 ppm. In case of biodiesel, the 60/40B indicates lowest amount of release of NO, approximately 240 ppm, followed by 50/50B, 336 ppm, 80/20B; 343 ppm, 70/30B, 374 ppm. Thus, application of biodiesel fuel releases lower amount of NO compared to diesel. Besides that, 60/40D and 60/40B release the lowest amount of NO for both diesel and biodiesel test fuel. The data findings were comparable to other published literatures, thus proving the significant effect of coating mixture to the emission of NO [13,15]. It was also significant that the piston coating is aimed to reduce wear and friction or to improve thermal efficiency with improved reduction of NO emission. The release of NO emission to the environment should be control as this gas has negative impact on the environment. Thus, achieving lower NO will ensure sustainability of the environment.

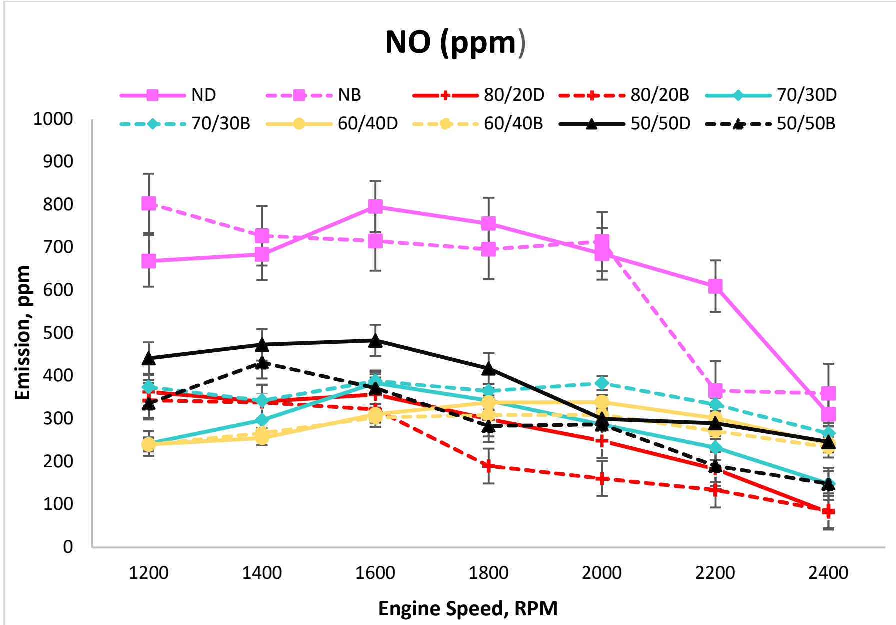

Figure 6. NO emission.

Besides, Figure 7 has illustrated the upshot of CO produced against the variable speed for coated and uncoated for both diesel and biodiesel test fuels. Figure 7 indicated that all the coated pistons recorded slightly higher amount release of CO compared to non-coated pistons. CO yielded lower with 10% (70/30) incremental of coating against a baseline coat of 60/40. CO yielded slightly higher with the decrement of 10% (50/50) of coating against a baseline coat of 60/40.

60/40D with 4.034% indicates lowest amount release of CO, followed by 70/30D; 4.277%, 80/20D; 6.024%, 50/50D; 7.446%. Then, for the biodiesel, 60/40B released lowest amount of CO, about 3.492%, followed by 70/30B; 3.896%, 80/20B; 4.826%, 50/50B; 4.058%. Overall biodiesel releases lower amount of CO compared to diesel.

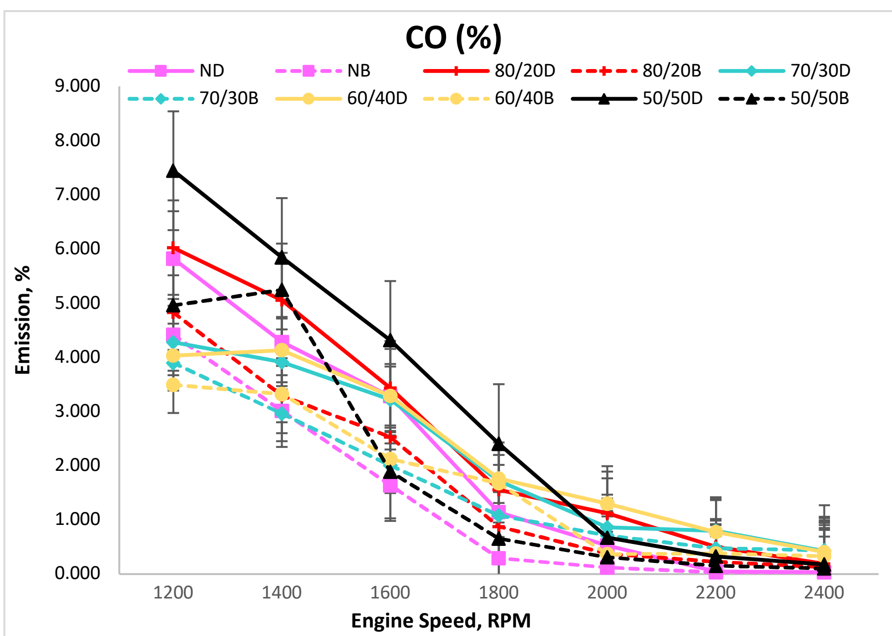

Figure 7. CO emission.

The CO emission was suggestively decreased with increase of speed, whereby when the engine running at optimum speed, the CO emission was suppressed to very minimum and almost eliminates its present. This test also proves that regardless of the piston coated with any coating, the emission of CO is well suppressed. CO is a dangerous and toxic gas and it is mandatory to ensure lower emission of CO to the environment as stipulated in local environmental statuary. Increasing of CO formation due to lower amount of oxygen presence in combustion chamber whereby leads to incomplete combustion. TBC enhanced the heat during compression stage by evaporation of the fuel to increase the surface area of fuels, hence enhancing the mix between fuel and air will reduce the CO formations [13]. Therefore, higher temperature enhanced HC chain breaking, thus leading to lower the CO emissions. Lower emission of CO when biodiesel was applied as a fuel was caused by higher oxygen content in the biodiesel that took part in the combustion, leading to complete combustion then lowered the CO emission [17]. CO emission occurs mainly due to fuel richness and unavailability of the oxygen in the combustion zone. In accordance with this, the diesel fuel resulted in higher CO emission compared to biodiesel, which can be stated as the result of the unavailability of the oxygen in the combustion zone [18].

Figure 8 depicts the trend of CO_2 emission at the variable speed for all coated pistons. All the coated pistons registered lowest amount release of CO_2 compared to non-coated pistons. CO_2 yielded higher with the 10% (70/30) incremental of coating against a baseline coat of 60/40. CO_2 yielded lower with the decrement of 10% (50/50) of coating against a baseline coat of 60/40.

At the maximum load, all coated pistons in the case of diesel, 70/30D with 4.91% indicate lowest amount release of CO_2, followed by 60/40D; 5.36%, 80/20D; 7.71%, 50/50D; 8.43%. Then, for the biodiesel, 60/40B released lowest amount of CO_2, about 6.05%, followed by 70/30B; 7.56%, 50/50B; 7.64%, 80/20B; 8.51%. Slightly higher CO_2 emission was compared with the CO emission, as complete combustion of fuel produces more CO_2, rather than CO for biodiesel.

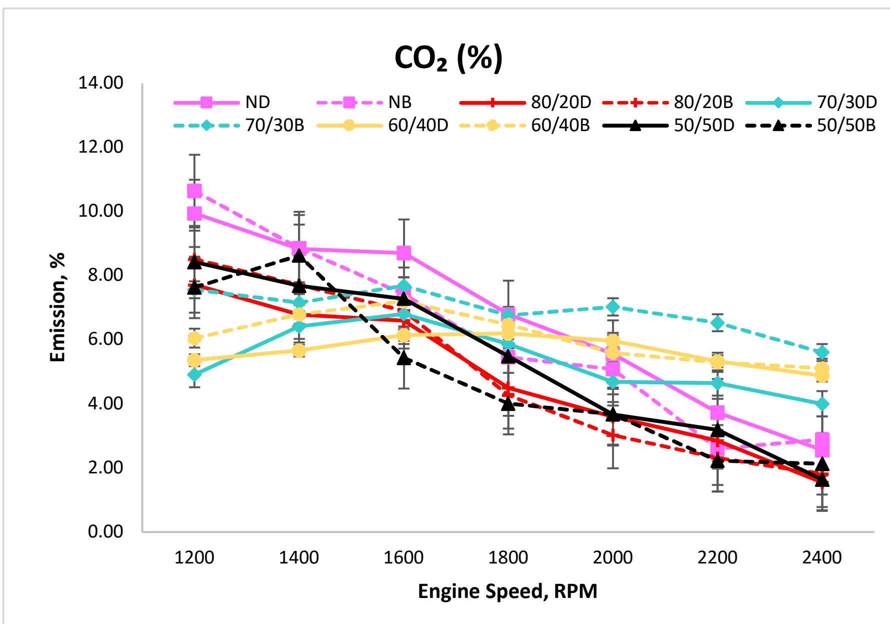

Figure 8. CO_2 emission at variable speed.

3.2. Engine Performance

On the other hand, the effects of TBC toward the engine performance were examined in terms of power generation, engine torque, BSFC, and BTE under various speeds using conventional diesel and biodiesel. Figure 9 indicates the power (kW) generated against variable speed illustrates the lowest trend for all coated compared to non-coated. Power yielded lower with the 10% (70/30) incremental of coating against a baseline coat of 60/40. Power yielded higher with the decrement of 10% (50/50) of coating against a baseline coat of 60/40.

For all coated pistons tested under diesel, the 80/20D with 3.84 kW indicates highest power, followed by 70/30D; 3.81 kW 50/50D; 3.64 kW, 60/40D; 3.41 kW. For those tested under biodiesel, the 70/30B with 4.04 kW indicates highest power, followed by 50/50B; 3.95 kW, 80/20B; 3.80 kW, 60/40B; 3.70 kW. Overall, biodiesel produced more power than diesel. This finding proved that modification of engine via TBC increased the power generated by biodiesel even though generally, less power was generated by biodiesel compared to diesel due to high kinematic viscosity and lower heating value of this renewable biodiesel [17,19].

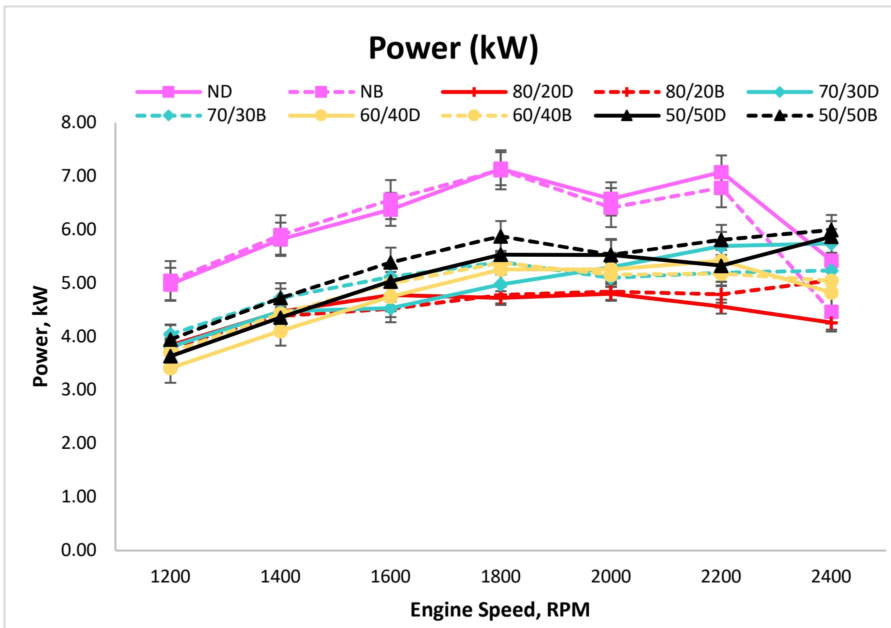

Figure 9. Power (kW) produced at various engine speed.

At maximum load, for Torque (Nm) generated against variable speed for Kubota Diesel Engine, Figure 10 depicts highest trend for all coated compared to non-coated. Torque yielded lower with the 10% (70/30) incremental of coating against a baseline coat of 60/40. Torque yielded higher with the decrement of 10% (50/50) of coating against a baseline coat of 60/40.

For all coated pistons tested under diesel (Figure 10), the 80/20D with 30.92 Nm indicate highest torque, followed by 70/30D;30.66 Nm 50/50D; 29.32 Nm, 60/40D; 27.46 Nm. For those tested under biodiesel, the 70/30B with 32.55 Nm indicates highest torque, followed by 50/50B; 31.80 Nm, 80/20B; 30.65 Nm, 60/40B; 29.74 Nm. Overall, biodiesel produced more torque than diesel. At all speed 50/50D and 50/50B maintain good stability and produce more torque for both diesel and biodiesel test fuel. This result also indicated the significant impact of TBC on the increasing torque on the engine. Researchers debated the main problem of application biodiesel and biofuel was less power and torque generated in the engine, which is caused by high viscosity and low calorimetric value of these fuels [17,20]. Therefore, the TBC seems to be one of the promising solutions to solve this problem, as suggested by [19,21,22].

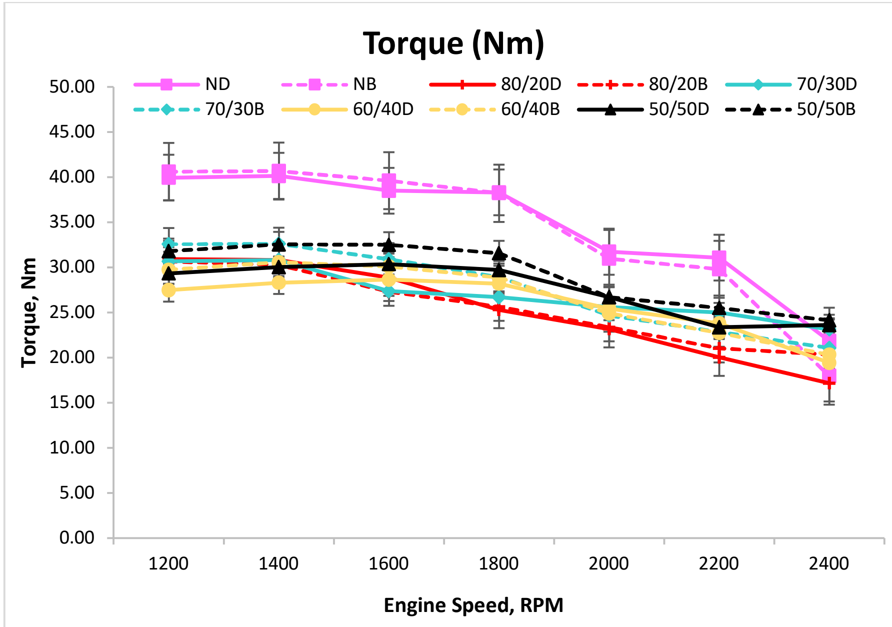

Figure 10. Engine torque at various engine speed.

At maximum load, BSFC effect against variable speed for Kubota Diesel Engine exemplifies the higher trend for all coated compared to non-coated. BSFC yielded higher with the 10% (70/30) incremental of coating against a baseline coat of 60/40. BTE yielded lower with the decrement of 10% (50/50) of coating against a baseline coat of 60/40.

The BSFC is one of vital parameters to evaluate the specific energy consumption and quality of the fuel [23]. Diesel fuel engine (Figure 11) indicates slightly higher value of BSFC with the increase of speed for both $Y_2O_3{\cdot}ZrO_2$-coated piston and Al_2O_3-coated piston when comparing to biodiesel. The coated piston delivers slight difference between coated engines of BSFC. The BSFC for biodiesel-fueled engine is generally higher than diesel-fueled engine due to the lower calorific values of palm oil biodiesel compared to conventional diesel fuel [17]. At maximum load, for BSFC effect against variable speed for Kubota Diesel Engine for all coated pistons tested under Diesel, the 80/20D with 557.96 g/kWh indicates lowest BSFC, followed by 70/30D; 743.26 g/kWh 50/50D; 901.29 g/kWh, 60/40D; 1030.78 g/kWh. For those tested under biodiesel, the 50/50B with 519.88 g/kWh indicates lowest BSFC, followed by 60/40B; 558.08 g/kWh, 80/20B; 707.22 g/kWh, 70/30B; 866.26 g/kWh. Overall, biodiesel contributes to lowest BSFC than diesel. At all speeds 50/50D and 50/50B maintain good stability and produce lower BSFC for both diesel and biodiesel test fuel. The BSFC was proportionally related to the temperature in the combustion chamber. Thus, this finding proved that the coating mixture had significant effect on the increasing of the temperature of combustion chamber. Higher temperature in the combustion chamber assisted to reduce ignition delay period and enhanced burning of fuel [9].

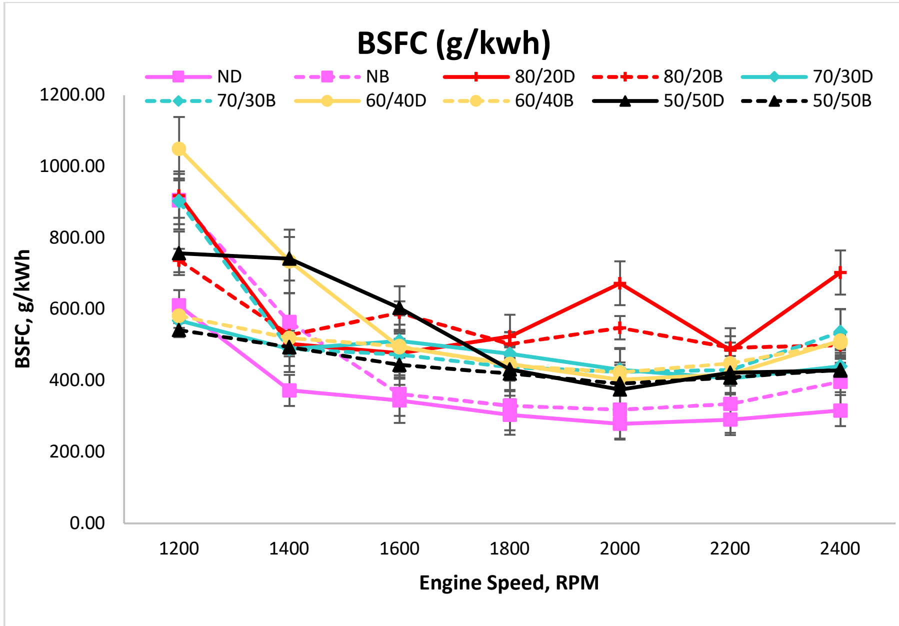

Figure 11. BSFC at various engine speed.

At maximum load, BTE effect against variable speed for Kubota Diesel Engine exemplifies the lowest trend for all coated compared to non-coated. BTE yielded lower with the 10% (70/30) incremental of coating against a baseline coat of 60/40. BTE yielded higher with the decrement of 10% (50/50) of coating against a baseline coat of 60/40. For all coated pistons tested under diesel, the 70/30D with 19.0% indicates highest BTE, followed by 50/50D; 14.3% 80/20D; 11.8%, 60/40D; 10.3% and 90/10D; 4.4%. For those tested under biodiesel (Figure 12), the 50/50B with 20.4% indicates highest BTE, followed by 60/40B; 19.0%, 80/20B; 15.0%, 70/30B; 12.2%, and 90/10B; 9.0%. Overall, biodiesel contributes higher BTE than diesel. At all speeds 60/40D and 50/50B maintain good stability and produce highest BTE for both diesel and biodiesel test fuel. For the rest of the parameters, 90/10B and 90/10D will not be evaluated as the value of the BTE is poor and the engine was underperforming with abnormal vibration. The combustion pressure of the 90/10D was much lower than the others because the heat loss through a piston crown was much higher. Hence, coating of 90% $Y_2O_3{\cdot}ZrO_2$ + 10% $Al_2O_3{\cdot}SiO_2$ is not a good coating to be considered for TBC. The BTE can be defined as the percentage of chemical energy from fuel converted into kinetic energy in the engine [9]. Selection of right coating mixture is vital as the TBC plays significant role in the conversion of chemical energy to kinetic energy. In addition, excess of oxygen content in the biodiesel generally contributes to achieving higher thermal efficiency [24]. Thus, the BTE of biodiesel recorded higher compared to diesel.

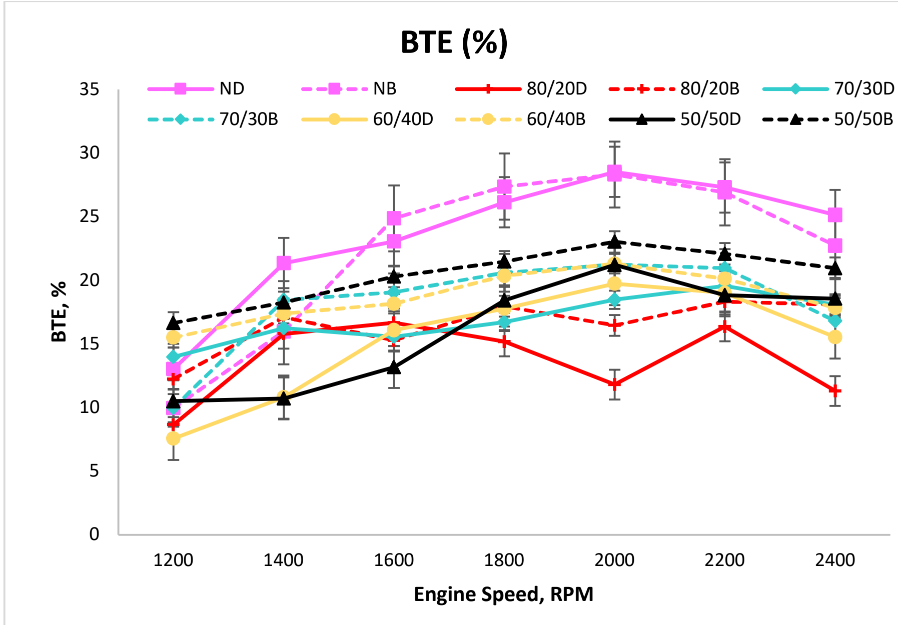

Figure 12. BTE percentage at various engine speed.

4. Discussion

The objectives of this study were to investigate the effect of engine performances and piston coated 90% $Y_2O_3 \cdot ZrO_2$ + 10% $Al_2O_3 \cdot SiO_2$, coated 80% $Y_2O_3 \cdot ZrO_2$ + 20% $Al_2O_3 \cdot SiO_2$, Coated 70% $Y_2O_3 \cdot ZrO_2$ + 30% $Al_2O_3 \cdot SiO_2$, coated 60% $Y_2O_3 \cdot ZrO_2$ + 40% $Al_2O_3 \cdot SiO_2$, coated 50% $Y_2O_3 \cdot ZrO_2$ + 50% $Al_2O_3 \cdot SiO_2$, and non-coated with test fuels of diesel and B100 palm biodiesel. In the present experimental work, Kubota RT125ES direct engine was used with eddy current dynamometer. The blend coating of $Y_2O_3 \cdot ZrO_2$ and $Al_2O_3 \cdot SiO_2$ was done using plasma spray coating. The performances of combustion and emission of coated and uncoated piston tested with diesel and B100 palm biodiesel are concluded as follow:

- For piston tested under diesel, the 80/20D with 18.98% indicates highest BTE. For those tested under biodiesel, the 50/50B with 20.37% indicates highest BTE. Overall, biodiesel contributes higher BTE than diesel. At all speeds 60/40D and 50/50B maintain good stability and produce highest BTE for both diesel and biodiesel test fuel. For the rest of the parameters, 90/10B and 90/10D will not be evaluated as the value of the BTE is poor and the engine was underperforming with abnormal vibration. Thus, 90% $Y_2O_3 \cdot ZrO_2$ + 10% $Al_2O_3 \cdot SiO_2$ coating mixture is not a good coating to be considered for TBC.
- For piston tested under diesel, the 80/20D with 557.96 g/kWh indicated lowest BSFC. For that tested under biodiesel, the 50/50B with 519.88 g/kWh indicates lowest BSFC. Overall, biodiesel contributes lowest BSFC than diesel. At all speed 50/50D and 50/50B maintain good stability and produce lower BSFC for both diesel and biodiesel test fuel.
- For piston tested under diesel, the 80/20D with 30.92 Nm indicates highest torque. For that tested under biodiesel, the 70/30B with 32.55 Nm indicates highest torque. Overall, biodiesel produced more torque than diesel. At all speeds 50/50D and 50/50B maintain good stability and produce more torque for both diesel and biodiesel test fuel.
- For all coated pistons tested under diesel, the 80/20D with 3.84 kW indicates highest power. For that tested under biodiesel, the 70/30B with 4.04 kW indicates highest power. Overall biodiesel produced power more than diesel. At all speed 50/50D and

50/50B maintain good stability and produce more power for both diesel and biodiesel test fuel.

- For all coated pistons tested under diesel, the 60/40D with 4.034% indicates lowest amount of CO released. For those tested under biodiesel, the 60/40B with 3.492% indicates lowest amount release of CO. At all speeds 60/40D and 60/40B maintain good stability and release lowest amount of CO for both diesel and biodiesel test fuel.
- For all coated pistons tested under diesel, the 70/30D with 4.91% indicates lowest amount release of CO_2. For those tested under biodiesel, the 60/40B with 6.05% indicates lowest amount release of CO_2. At all speeds 60/40D and 50/50B maintain good stability and release lowest amount of CO_2 for both diesel and biodiesel test fuel.
- For all coated pistons tested under diesel, the 60/40D with 240 ppm indicates lowest amount release of NO. For those tested under biodiesel, the 60/40B with 240 ppm indicates lowest amount of NO release. Overall, biodiesel releases lower amount of NO compared to diesel. At all speeds 60/40D and 60/40B maintain good stability and release lowest amount of NO for both diesel and biodiesel test fuel.
- For all coated pistons tested under diesel, the 70/30D with 112 ppm indicates lowest amount release of HC. For those tested under biodiesel, the 60/40B with 78 ppm indicates lowest amount release of HC. At all speeds 60/40D and 60/40B maintain good stability and release lowest amount of HC for both diesel and biodiesel test fuel.

5. Conclusions

From this study, coating mixture of 60% $Y_2O_3{\cdot}ZrO_2$ + 40% $Al_2O_3{\cdot}SiO_2$ has produced an overwhelming result in term of reduction of NO, CO, and HC emission but not so promising in term of performance. On the other hand, 50% $Y_2O_3{\cdot}ZrO_2$ + 50% $Al_2O_3{\cdot}SiO_2$ showed better performance and slightly higher NO compared to 60% $Y_2O_3{\cdot}ZrO_2$ + 40% $Al_2O_3{\cdot}SiO_2$. Thus, in the future studies, narrower gap between 50% $Y_2O_3{\cdot}ZrO_2$ + 50% $Al_2O_3{\cdot}SiO_2$ and 60% $Y_2O_3{\cdot}ZrO_2$ + 40% $Al_2O_3{\cdot}SiO_2$ might need to be explored in order to obtain better blend between $Y_2O_3{\cdot}ZrO_2$ and $Al_2O_3{\cdot}SiO_2$. In general, all the coated pistons performed excellent in reducing NO compared to non-coated pistons; however, trade off with a lower engine performance compared to non-coated pistons. The author suggested, further studies might be explored in SiO_2 addition in the blend as it reduces NO formation. A complete study of partially coated (piston crown), fully coated (piston crown, valves, combustion liner, combustion top head), thickness effect of coating might be needed to explore.

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