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Performance of Tire Pyrolytic Oil and its Blends with Biodiesel in Diesel Engine

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ABSTRACT
Microwave-assisted pyrolysis of scrap automotive tires allows recovery of energy and useful materials, such as pyrolytic oil, char and gases. Scrap tire were being heated in inert atmosphere at temperature between 400 and 600°C to produce liquid fuel. Tire pyrolytic oil obtained possessed high calorific value in range of 42.09 – 43.67MJ/kg. The benefit of this thermal treatment was conversion of waste material into high calorific pyrolytic oil, which could be burnt directly in an unmodified diesel engine. Moreover, tire pyrolytic oil was blended with petroleum diesel and biodiesel at different volume ratio for performance and exhaust emissions study. Engine performance such as engine torque, engine brake power, brake specific fuel consumption and brake thermal efficiency were examined with different blend ratio of fuel. Results showed that neat tire pyrolytic oil give an average of 7.93% lower torque and emission of carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x) and sulphur dioxide (SO_2), at an average of 207.4%, 201.7%, 1301.5% and 580.7% higher, respectively than that of petroleum diesel fuel. Meanwhile, neat tire pyrolytic oil showed an average of 12.84% higher torque and emission of carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x) and sulphur dioxide (SO_2), at an average of 369.6%, 1601.9%, 46.36% and 640.3% higher, respectively than that of palm biodiesel fuel.

Keywords**:** *Scrap automotive tires, Microwave pyrolysis, Biodiesel, Diesel engine, Engine performance*

1. INTRODUCTION

Pyrolysis oil can be produced by pyrolysis of scrap automotive tires. Studies of Undri et al.,[1][2] stated that pyrolysis of rubber is a method of recovering hydrocarbon liquid which has high calorific value and can be used as petroleum products. It is conducted under absence of oxygen. In renewable energy industry, tire pyrolysis oil can be partially used to replace commercial diesel as tire has more than 90% organic materials and has high remarkable energy content with calorific value up to 36.8 MJ/kg [3][4][5], compared to conventional diesel fuel that has 45.1MJ/kg [6] and coal which has 18.6 - 27.9 MJ/kg [7].

In the current experiment, the performance of tire pyrolytic oil in diesel engine was evaluated by using its blends at different ratio with biodiesel. The engine performance and exhaust gas emission of different blends ratio of tire pyrolytic fuel with biodiesel in a diesel engine were investigated at five different engine speeds (1400, 1800, 2200, 2600, and 3000 rpm) and compared with neat diesel fuel operation.

2. METHODOLOGY

2.1. Microwave tire pyrolysis system.

Scrap tire were shredded into smaller form with all steel wire and polymeric fiber removed. The pyrolysis process was performed using a laboratory scaled microwave system. The microwave assisted pyrolysis system was modified from a conventional microwave with maximum heating power of 800W using a cylindrical quartz reactor of 150 mm in height and 100 mm in diameter.

2.2. Tire pyrolytic liquid, Biodiesel (Palm Methyl Ester) and Diesel Fuel

The tire pyrolytic liquid and its blends were characterized for its fuel properties, including elemental composition, H/C ratio, calorific value, density, viscosity and etc. The fuel properties were compared with that of petroleum diesel fuel.

Table 1. Physical characteristics of pyrolytic oil, petroleum diesel and biodiesel

Content analysis wt%	Waste tyre pyrolysis oil	Petroleum diesel fuel [8]	Biodiesel (Palm Methyl Ester)
Carbon	85.13	84.76	76.90
Hydrogen	10.06	14.96	12.26
Nitrogen	0.63	0.01	0.15
Oxygen	2.07	0.00	14.59
Sulfur	2.68	0.28	0.15
C/H	8.46	5.67	6.27
Ash	0.10	-	-
Calorific value (MJ/kg)	42.09 – 43.67	45.50	39.59
Kinematic viscosity at 50ºC	6.53	-	4.62
Density at 15ºC, kg/L	0.96	0.84	0.87

Characterization results showed that neat pyrolytic oil had viscosity at 6.53 cST at 35°C and density of 0.96kg/L at 15°C. From literature, viscosity and density of pyrolytic liquid was slightly higher than conventional petroleum diesel fuel [6]. Pyrolytic oil had calorific value in range of 42.09–43.67 MJ/kg, this property was a value-added feature for use in an unmodified engine. An ideal physical characteristic of pyrolytic liquid increases the possibility of directly using pyrolytic liquid or of blending it with petroleum diesel fuel [9].

2.3 Diesel engine test bed experiments

The diesel engine used was a Yanmar L70N6 air-cooled diesel engine with displacement of 0.320L, capable to deliver maximum output of 4.9kW at 3600 rpm. The bore and stroke of engine were 78 and 67 mm, respectively. An electronic dynamometer was coupled to measure torque and speed of diesel engine. The tire pyrolytic oil was blended with biodiesel at different percentage by volume 0 vol%, 25vol%, 50vol%, 75vol% and 100vol%, and are known as B100, P25B75, P50B50, P75B25 and P100, respectively. Meanwhile, the tire pyrolytic oil was blended with fuel diesel at different percentage by volume 0 vol%, 25vol%, 50vol%, 75vol% and 100vol%, and are known as D100, P25D75, P50D50, P75D25 and P100, respectively for comparison. Similarly, in the research of İlkılıç and Aydın,[10] tire pyrolytic oil was blended with diesel fuel at percentage of 5vol%, 10vol%, 15vol%, 25vol%, 35vol%, 50vol%, 75vol% and 100vol% (pure tire pyrolytic oil) [10]. The diesel engine was first run with neat diesel fuel to obtain the baseline data as reference results, such as torque, engine speed, fuel consumption, exhaust temperature and exhaust emissions. The quality of exhaust emission was also inspected with neat diesel fuel during the series of experiments.

3. RESULTS AND DISCUSSION

3.1 Engine performance

This section studied and discuss about performance results of tire pyrolytic oil blend in an unmodified engine. The main purpose was to understand the effect of different blend ratio of tire pyrolytic oil in diesel engine. Unlike conventional petroleum diesel fuel, tire pyrolytic oil possessed different physiochemical properties. So, relevant researches on various blends ratio of tire pyrolytic oil in diesel engine were performed as in previous researches [10][11].

3.1.1 Engine Torque

A comprehensive diesel engine performance test was conducted to understand the effect of tire pyrolytic oil/ biodiesel blends and results were compared with tire pyrolytic oil/diesel blends. For this objective, several fuel blends with different percentage of tire pyrolytic oil at containing 0vol%, 25vol%, 50vol%, 75vol% and 100vol% were prepared.

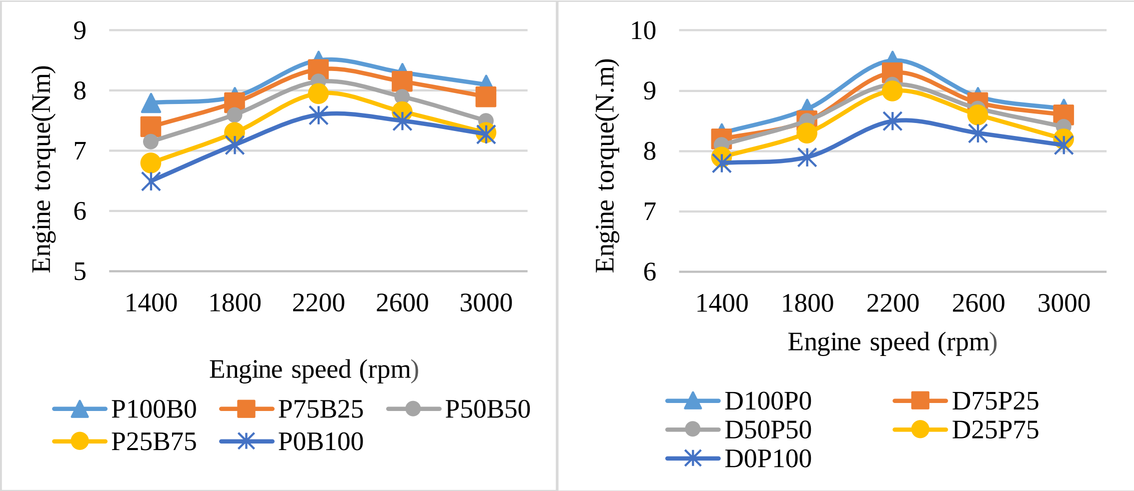

Figure 1 Variation of engine torque with engine speed for pyrolysis oil blends with biodiesel (left), variation of engine torque with engine speed for pyrolysis oil blends with diesel fuel (right).

Engine test were performed at five different speed of 1400, 1800, 2200, 2600 and 3000 rpm. Preliminary result showed neat tire pyrolytic oil (P100B0) delivered the highest torque at all speed with blends of biodiesel fuel. Highest torque at value of 8.5Nm was achieved by P100B0, however torque value of output torque deteriorated at higher percentage of biodiesel. In set experiment of tire pyrolytic oil/biodiesel blends, engine torque decreased as the percentage of biodiesel increase. Neat biodiesel D0B100 showed the highest torque at value of 7.6Nm, the average torque was 12.84% lower than that of neat pyrolysis oil. In set experiment of tire pyrolytic oil/diesel blends, neat tire pyrolytic oil showed the lowest torque among all speed as compared to that of petroleum diesel fuel. İlkılıç and Aydın [10] stated that the lower calorific value of pyrolytic oil blend had caused lower output torque than that of pure petroleum fuel.

3.1.2 Brake specific fuel consumption

Brake specific fuel consumption (BSFC) is one the most precise parameter to measure the amount of fuel consumed by the engine to produce a unit amount of work and to compare fuel economy when two different of fuel were blended, since two different fuel possessed different density and calorific value.

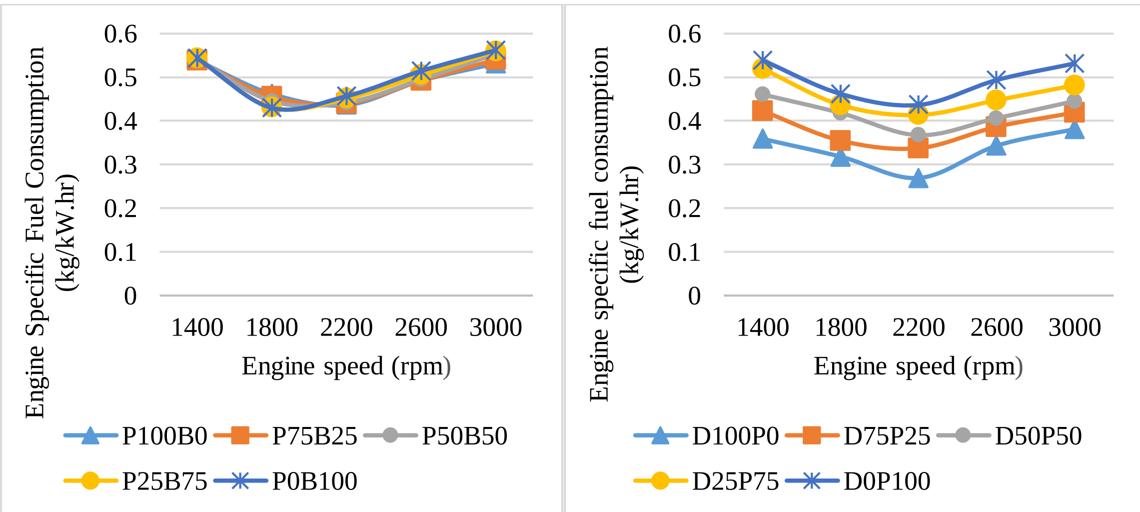

Figure 2 Variation of engine brake specific fuel consumption with engine speed for pyrolysis oil blends with biodiesel (left), variation of engine brake specific fuel consumption with engine speed for pyrolysis oil blends with diesel fuel (right).

Figure 2 shows the variation of engine brake thermal efficiency (%) with engine speed for pyrolysis oil blends with biodiesel. Trend of BSFC showed neat tire pyrolysis oil (P100) consumed the lowest amount of fuel at engine speed above 2200rpm. However, neat biodiesel (B100) consumed the least fuel at engine speed of 1800 rpm. The best BSFC achieved by P100 was 0.44kg/kWhr at 2200 rpm. Neat diesel fuel (D100) delivered the best result as the value of BSFC were the lowest among all engine speed. In experiment with tire pyrolytic oil/biodiesel blends, fuel blends with higher percentage of biodiesel had higher BSFC due to lower calorific value of biodiesel. In experiment with tire pyrolytic oil/diesel blends, fuel with higher percentage of tire pyrolytic oil showed the highest BSFC as compared to that of neat diesel fuel. All results were reasonable where more fuel was required at higher percentage of tire pyrolysis oil/diesel blends to produce a unit power of work. This was caused by the lower calorific value and higher density of tire pyrolytic oil. BSFC of an engine test is highly affected by engine operation condition, fuel kinematic viscosity, fuel calorific value and density [10][12], where effects of each feature might offset each another.

Engine torque and specific fuel consumption of blends fuel are shown in Figures 1 and 2. Pyrolytic oil shows better engine performance than biodiesel in term of higher calorific value and delivered higher engine output torque and engine brake power.

3.1.3 Brake thermal efficiency (%)

Variation of brake thermal efficiency (BTE) with engine speed for blends of pyrolytic oil and biodiesel fuel is shown in Figure 3. All fuel blends shows an increasing trend of BTE at lower engine speed.

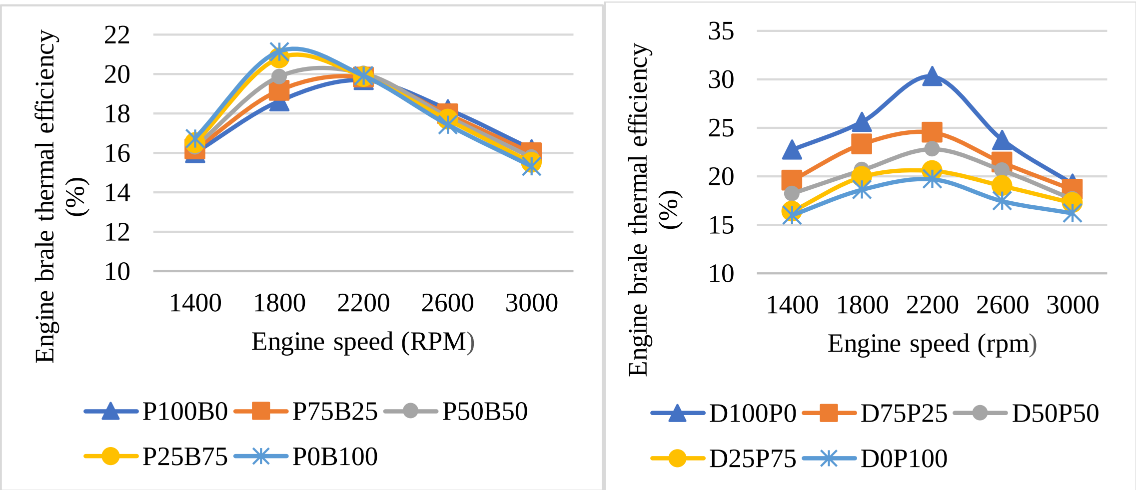

Figure 3 Variation of brake thermal efficiency with engine speed for pyrolysis oil blends with biodiesel (left), variation of brake thermal efficiency with engine speed for pyrolysis oil blends with diesel fuel (right).

Highest BTE was achieved by all fuel blend at engine speed of 1800rpm. However, BTE of all fuel blend ratio were deteriorated at higher engine speed. Similar trend of BTE was observed in previous study, where value of BTE was in an increasing form at lower engine speed and decreased at higher engine speed above 2800rpm [13]. In the experiment, neat diesel fuel delivered the highest brake thermal efficiency among all fuel types. High viscosity and density of both fuels had resulted in poor volatility and atomization, consequently a more ununiformed combustion and lower BTE than that of pure petroleum diesel fuel. At lower engine speed, P0B100 showed a higher BTE at lower engine speed. However, P100B0 showed a slightly higher BTE than that of P0B100 at higher engine speed. The average BTE of P100B0, P75B25, P50B50, P25B75 and P0B100, were 17.75%, 17.83%, 17.97%, 18.80% and 18.11%, respectively. All results of average BTE were below 20%. The poor performance of fuel with low of BTE for pyrolytic oil and biodiesel blend was attributed to poor fuel atomization due to high kinematic viscosity and density of both fuels [13].

3.2 Exhaust emission

Combustion of petroleum-based fuel emitting pollutant emission and toxic gases that were harmful to environment and human being. Pollutant emitted from exhaust emission can be grouped into two major categories: primarily pollutants and secondary pollutants. Only primarily pollutants such as carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), are considered in this study and particulate matter (PM) as secondary pollutant are not considered in this study.

3.2.1 Carbon monoxide (CO)

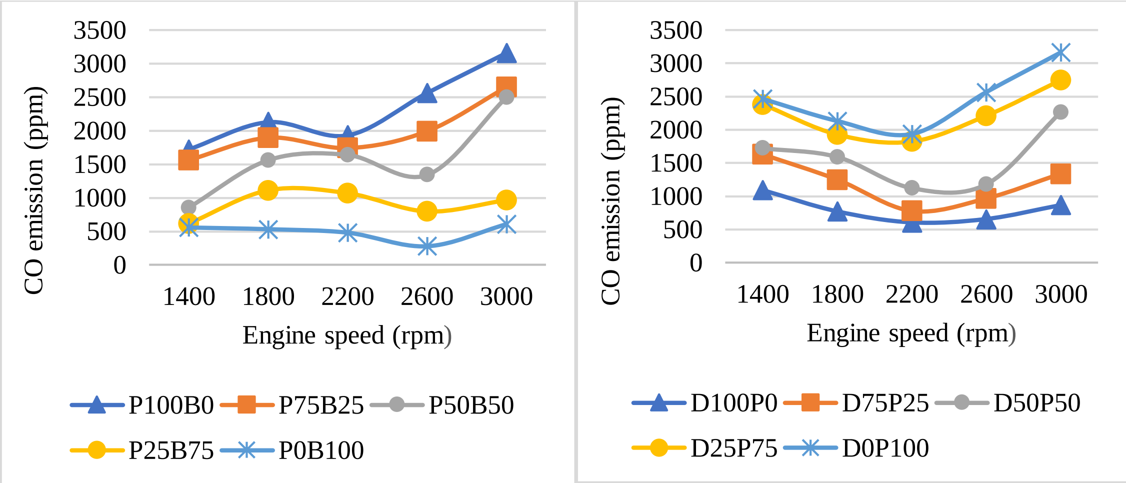

Figure 4 Carbon monoxide (CO) emission with engine speed for blends of pyrolytic oil and diesel fuel (left), carbon monoxide (CO) emission with engine speed for blends of pyrolytic oil and diesel fuel (right).

Variation CO emission with engine speed for blends of pyrolytic oil and biodiesel fuel is shown in Figure 3.4. Pure pyrolytic oil (P100B0) showed the highest concentration of CO emission at all engine speed, with average 207.4% higher emission than pure diesel fuel. Meanwhile, pure biodiesel (P0B100) showed the lowest concentration of CO emission at all speed of engine. The average concentration of CO emission for P100B0, P75B25, P50B50, P25B75 and P0B100, were 2301.8ppm, 1969.2ppm, 1581.6ppm, 910.4ppm and 490.2ppm. The higher fuel density of pyrolytic oil blend caused higher mass of fuel being injected into combustion cylinder, the rich fuel-air ratio condition had increased the CO emission for higher ratio of pyrolytic fuel blend, this situation was more significant at higher engine speed [10]. For study with tire pyrolytic oil/diesel blends, neat diesel fuel emitted the lowest CO among all fuel blends. This is because neat diesel fuel allowed more complete combustion.

This situation agreed with results of another author, where higher pyrolytic fuel blend discharged higher concentration of CO emission [14] At higher engine speed beyond optimum, high trend of carbon monoxide emission were caused by higher fuel consumption. Besides that, the high fuel density of pyrolytic fuel blend caused higher mass of fuel being injected into combustion cylinder, the rich fuel-air ratio condition had increased the CO emission for higher ratio of pyrolytic fuel blend [10] . Fuel with higher blend ratio of biodiesel showed lower emission of CO for all engine speed. This was because fuel combustion was improved and more complete because of higher oxygen content in biodiesel. Elemental analysis showed 14.597% of oxygen in biodiesel fuel. Meanwhile, oxygen content in pyrolytic fuel was at maximum of 6.20%.

3.2.2 Hydrocarbon compound (HC)

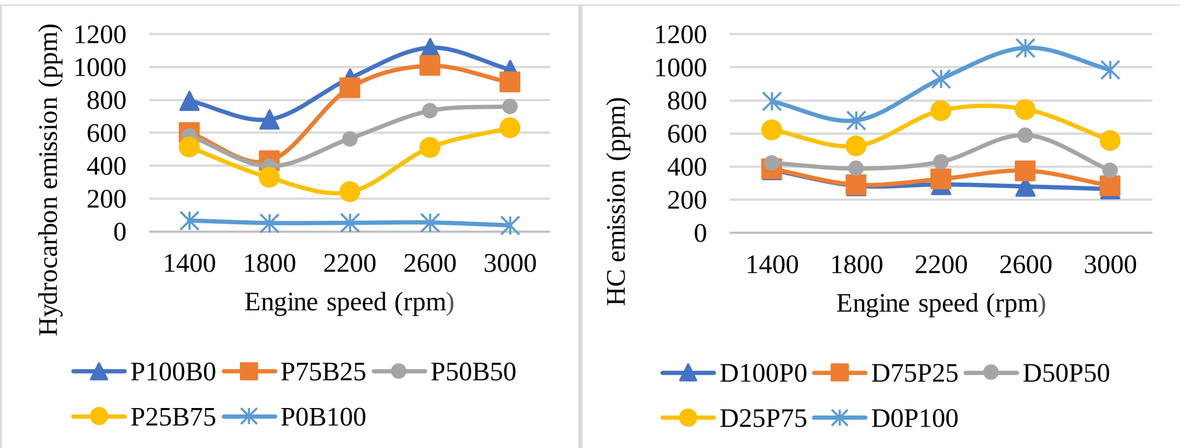

Figure 5 Hydrocarbon (HC) emission with engine speed for blends of pyrolytic oil and diesel fuel (left), Hydrocarbon (HC) emission with engine speed for blends of pyrolytic oil and diesel fuel (right).

Variation hydrocarbon (HC) emission with engine speed for blends of pyrolytic oil and biodiesel fuel is shown in Figure 5. Pure pyrolytic fuel (P100B0) showed the highest concentration of HC emission among all fuel blend for all engine speed. However, pure biodiesel (P0B100) showed the lowest concentration of HC emission. The average HC emission of P100B0, P75B25, P50B50, P25B75 and P0B100, were 902ppm, 764.6ppm, 607ppm, 444.4ppm and 53ppm. The high level of HC emission of P100B0 and P75B25 was due to high level of aromatic compound in pyrolytic oil, these aromatic compounds resulted in high emission of unburnt hydrocarbon [14][15]. The high concentration of HC emission in higher blend ratio of pyrolytic oil was due to high fuel density blend resulted in higher mass of fuel being injected into engine combustion cylinder, the high fuel-air ratio had discharged higher unburnt HC [10]. Higher blend ratio of biodiesel discharged lower concentration of HC emission because biodiesel had high oxygen at percentage of 14.597%, which encourage more complete fuel combustion [16]. Meanwhile, previous researches stated a decrement of HC emission was shown as blend ratio of biodiesel was getting higher [13][17].

3.2.3 Nitrogen oxides (NO_x)

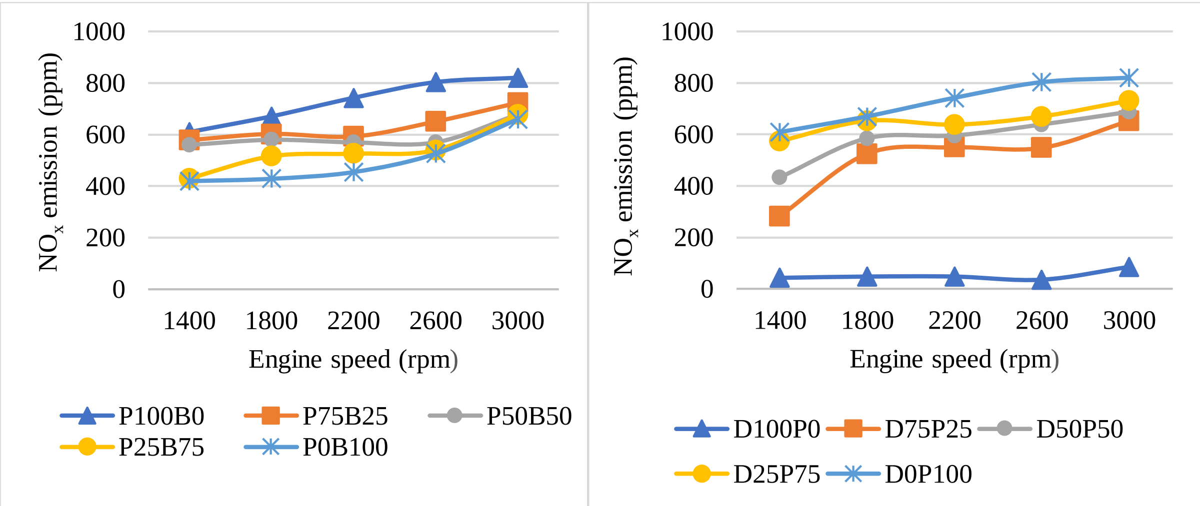

Figure 6 Nitrogen oxides (NO_x) emission with engine speed for blends of pyrolytic oil and diesel fuel (left); Nitrogen oxides (NO_x) emission with engine speed for blends of pyrolytic oil and diesel fuel (right).

Variation nitrogen oxides (NO_x) emission with engine speed for blends of pyrolytic oil and biodiesel fuel is shown in Figure 6. Pure pyrolytic oil (P100B0) showed the highest concentration of NO_x emission among all fuel blend for all engine speed. Meanwhile, pure biodiesel (P0B100) showed the lowest concentration of NO_x emission among all fuel types. The average NO_x emission of P100B0, P75B25, P50B50, P25B75 and P0B100, were 411.6ppm, 372ppm, 281.2ppm, 94ppm and 55.6ppm. This finding agreed with several results reported in literature [14][15]. The high emission of NO_x emission was attribute to higher density of pyrolytic fuel so higher mass of pyrolytic fuel was injected into the combustion cylinder [15]. Higher blend ratio of pyrolytic oil had more aromatic compound that resulted in higher fuel combustion temperature and discharging higher concentration of NO_x emission. Previous studies stated that, higher blend ratio of pyrolytic oil had poorer fuel atomization ability and lower cetane number resulted in prolonged ignition delay [10], consequently rate of thermal release was maximized and allowed higher temperature that lead to higher NO_x emission. In this study, concentration of NO_x emission showed an increasing trend as increment of both engine speed and temperature of fuel combustion in engine cylinder [14].

3.2.4 Sulfur dioxide (SO_2)

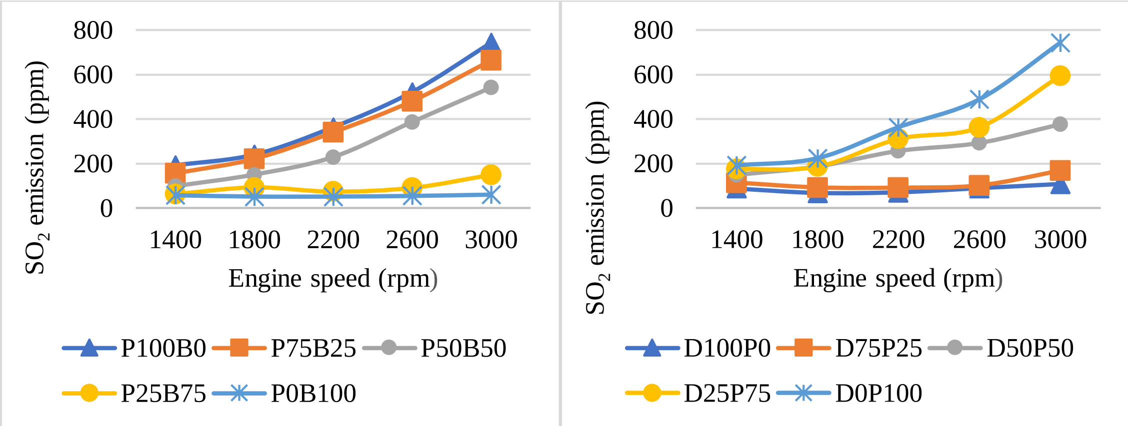

Figure 7 Sulfur dioxide (SO_2) emission with engine speed for blends of pyrolytic oil and diesel fuel (left); Sulfur dioxide (SO_2) emission with engine speed for blends of pyrolytic oil and diesel fuel (right).

Variation of sulfur dioxide SO_2 emission with engine speed for blends of pyrolytic oil and biodiesel fuel is shown in Figure 7. Pure pyrolytic oil P100 showed the highest concentration of SO_2 emission for all fuel types. In the following, P75B25 showed the second highest concentration of SO_2 emission. Meanwhile, pure biodiesel showed the lowest SO_2 emission among all fuel blend ratio. The average SO_2 emission of P100B0, P75B25, P50B50, P25B75 and P0B100, were 411.6ppm, 372ppm, 281.2ppm, 94ppm and 55.6ppm. This indicated that fuel with higher blend ratio of pyrolytic fuel discharge higher concentration of SO_2 emission. Previous study stated that concentration of SO_2 emission was linear with blend ratio of pyrolytic oil since sulfur content in pyrolytic is higher than another tested fuel [10]. Similar result was shown, where pyrolytic oil with blend ratio above 50vol% discharged higher SO_2 emission [10]. Besides that, higher SO_2 emission was discharged at higher engine speed due to lower air-fuel ratio and volumetric efficiency [10]. Neat diesel fuel and biodiesel showed the lowest concentration of SO_2 compared to that of neat tire pyrolytic oil. SO_2 is formed by sulfur content in the fuel after combusted at high temperature of combustion cylinder, consequently SO_2 emission is linear with presented sulfur content in the fuel.

4. CONCLUSIONS

In conclusion, neat and blends of tire pyrolytic oil could be used in diesel engine without any engine modification. Lower blends of tire pyrolytic oil showed higher fuel performance after neat petroleum diesel fuel. However, output torque and engine brake power decreased at higher blend ratios of tire pyrolytic oil as compared to petroleum diesel. Result showed neat tire pyrolytic oil (P100B0) delivered the highest torque at all speed with blends of biodiesel fuel. Highest torque at value of 8.5Nm was achieved by P100B0, however torque value of output torque deteriorated to 7.6N.m at higher percentage of biodiesel. In average, neat tire pyrolytic oil showed an average of 12.84% higher torque than biodiesel due to higher calorific value. Also, neat tire pyrolytic oil shows an average 7.93% lower torque compared to that of petroleum diesel fuel. Higher blend ratios of tire pyrolytic oil with petroleum diesel show lower engine performance due to the higher viscosity and lower calorific value of pyrolytic oil blend. BSFC study showed neat tire pyrolysis oil (P100) consumed the lowest amount of fuel at engine speed above 2200rpm. However, neat biodiesel (B100) consumed the least fuel at engine speed of 1800 rpm. The best BSFC achieved by neat pyrolytic oil was 0.44kg/kWhr at 2200 rpm. In study of tire pyrolytic oil/biodiesel blends, fuel blends with higher ratio of biodiesel had higher BSFC due to lower calorific value of biodiesel. At lower engine speed of 1800rpm biodiesel(B100) shows highest BTE at 21.14%, however fuel blends. However, BTE deteriorated to below 20% at higher engine speed for all pyrolytic and biodiesel oil blend because of poor fuel atomization due to high kinematic viscosity and density. High blend ratio of pyrolytic oil combustion in engine shows high emission of carbon monoxide, nitrogen oxides, hydrocarbon and sulfur dioxide. Discharge of high emission of sulfur dioxide (SO_2) with pure pyrolytic fuel was due to high sulfur content in tire pyrolytic oil. To lower the emission of SO_2 could be achieved by lowering the sulfur content during the MW pyrolytic process. Pyrolytic oil shows better engine performance than biodiesel in term of higher calorific value and delivered higher engine output torque and engine brake power. However, high blend ratio of pyrolytic oil shows poorer results of gas emission than biodiesel. Hydrocarbon and carbon monoxide emission were lower in biodiesel than that of pyrolytic oil, because biodiesel had higher composition of oxygen content at value of 14.6%. Blend of pyrolytic oil and biodiesel can be combusted in diesel engine and no significant engine problem was observed during the experiment. However, further research on pyrolytic oil is recommended for improving of fuel properties in terms of reducing the viscosity and sulfur content of fuel.

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