Performance Analysis of a Direct Injection Diesel Engine Using Biodiesel and Additives

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ABSTRACT

Combustion in diesel engines release harmful gases leading to air pollution. Biodiesel, a mixture of petroleum-based and plant-derived hydrocarbon, is known for its potential to reduce harmful emissions in diesel engines. However, one of the main problems with biodiesel is high carbon deposition due to very long carbon chain content. Additives are used as carbon deposition breaker for the engine. This paper presents the effects of such additives on engine performance fuelled with oil palm biodiesel. A single cylinder direct injection diesel engine, YANMAR TF90 were run with different blends of diesel-biodiesel and 2.0ml Decarbonising High Performance (DHP) as additives. Results of the in-cylinder pressure were then analyzed to determine the combustion characteristics. Biodiesel produced lower gas pollutant compared to pure diesel, but due to high viscosity and low heating value, the engine performance was lower than diesel. However, the viscosity reducer and heating value improver additive were found to improve engine performance.

Keywords: *Direct Injection, Biodiesel, Additives, Performance, Heat Release Rate*

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Introduction

Diesel engine has been widely used in generators, construction, industrial, agricultural and automotive industries. It is able to produce a wide range of power for commercial light vehicles as well as megawatts power generators. An alternative to diesel has been sought for the past 20 years to reduce the amount of pollution, lessen dependency on external supply and alleviate the burden of fuel price hikes [1]. There is plenty of oil palm supply in Malaysia. Based on statistics from the Malaysian Palm Oil Board (MPOB), oil palm plantations in Malaysia cover a total area of 5.39 million hectares, with oil palm production reaching 20000 million tonnes (the highest production recorded by the country). In addition, oil palm plantation covers 16% of the total plantation land area of 32.98 million hectares in Malaysia [2]. As indicated in the Economic Transformation Program (ETP) launched in 2010, Malaysia aspires to rapidly develop its economy and become a high-income nation by 2020. Hence, oil palm industry is one of the sectors with the potential to contribute to such transformation besides petroleum and gas, education, health and tourism sectors. It is believed that oil palm products have the potential to create a balance in the country's economic development.

Emission of gases such as CO, NO_x, CO_2, sulphur and soot needs to be controlled to reduce environmental damage which will lead to problems such as global warming, acid rain and air pollution. Such problems in turn can cause complications especially to human health. The release of harmful gases from diesel engine combustion occurs due to incomplete combustion. It is believed that by blending biodiesel in diesel fuel, the harmful gas emission can be reduced due to high percentage of oxygen contents in biodiesel. Blending biodiesel can therefore lead to complete combustion and reduce impacts to the environment. In fact, studies have shown that the release of CO decreases with the increasing percentage of biodiesel [3].

Biodiesel fuel is known as fatty acid methyl ester (FAME) produced from fatty acid products including plant oil through the process of transesterification. The process occurs where plant oil is obtained from bio-resources and reacts with alcohol with the help of catalyst to produce fatty acid methyl ester and glycerol. Biodiesel fuel is rich in oxygen content and has the capability to produce complete combustion. However, biodiesel fuel has higher viscosity and density which may cause engine problems including injector failure, corrosion of copper, high carbon deposits and engine components wear [4].

The density of biodiesel is higher than diesel due to large amounts of oxygen atom in biodiesel which has high mass [5]. Fuel additives added to biodiesel can reduce the density and viscosity thus leading to better atomization. As a result, the use of additives can improve engine performance as well as fuel consumption [6]. Engine performance can be improved through complete combustion, which can supposedly be achieved by mixing fuel additives. The chemical content of additives is unknown due to insufficient data from manufacturer. Therefore, a change in performance only can be compared and analysed when additives are mixed and tested in diesel engine.

Hence, the following experiment was conducted to study engine performance using diesel and biodiesel fuel, plus the addition of additives. Combustion characteristics for different types of diesel and biodiesel fuel mixture which included in-cylinder pressure and heat release rate during combustion were then studied. Engine performance also includes brake power, brake thermal efficiency and brake specific fuel consumption. Combustion characteristics signify the injection period and start of ignition in cylinder. On the other hand, Heat Release Rate (HRR) is the amount of heat released in cylinder for every crank angle rotation of shaft. The highest energy gradient difference for HRR or in-cylinder pressure indicates the ignition time of each cycle due to the large energy produced by the fuel. The heat release rate (kJ/CA) for diesel is higher than biodiesel due to higher calorific value in diesel which produces more energy [7].

Methodology

Fuel Preparation

Eight different mixtures of diesel, diesel with biodiesel, and diesel with biodiesel and additives were prepared. The biodiesel used in this experiment was palm oil methyl ester that underwent transesterification process. Both diesel and palm oil were mixed in the same container to produce the required percentage. The mixture was stirred at the speed of 450 rpm using magnetic stirrer for 15 minutes and was left for 15 minutes to ensure it reached chemical equilibrium state. The additive used was Decarbonising High Performance (DHP), which is used to break down carbon deposition. 2.0 ml of DHP was used in diesel and palm biodiesel blends as explained in Table 1.

Table 1: Biodiesel, diesel and additive blend percentages

No.	Blend percentage	Acronyms
1	Diesel	Diesel
2	Diesel + Additive 2.0 ml	Diesel + ADDT
3	Palm biodiesel 10% + Diesel 90%	PB10
4	Palm biodiesel 10% + Diesel 90% + Additive 2.0 ml	PB10 +ADDT
5	Palm biodiesel 20% + Diesel 80%	PB20
6	Palm biodiesel 20% + Diesel 80% + Additive 2.0 ml	PB20+ADDT
7	Palm biodiesel 30% + Diesel 70%	PB30
8	Palm biodiesel 30% + Diesel 70% + Additive 2.0 ml	PB30 +ADDT

Engine test

YANMAR TF 90 engine with a dynamometer connected to it was used to test engine performance using different types of fuel. The testbed comprised a meter panel that showed the reading of speed, torque, and the volume flow meter which indicated the amount of fuel used during the test run. There was a load bank control from 1 kW to 5 kW. The engine was a single cylinder direct injection compression ignition.

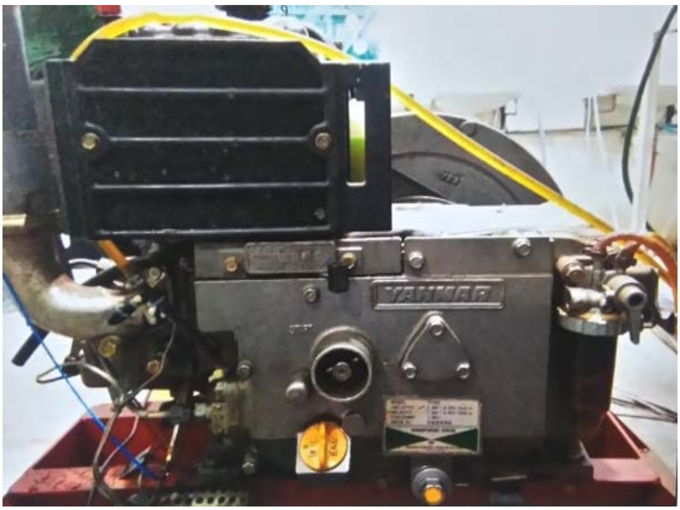

Figure 1: YANMAR TF90 engine

Table 2 and Table 3 show specifications of the engine and dynamometer as used in the experiment.

Table 2: Engine Specifications (Source: YANMAR DIESEL ENGINE CO.LTD.)

Detail	**Specification**
Model	YANMAR TF90
Number of cylinders	1
Cylinder Bore x Stroke (mm)	85 x 87
Total volume (litres)	0.493
Compression ratio	18.0
Continuous Rated Output, hp/rpm (kW)	8.5/2400 (6.3)
Max. torque (Nm/rpm)	3.4/1600
Colling water capacity (liter)	8.0
Cooling system	Hopper (H)

Table 3: Eddy Current Dynamometer Specifications

Details	**Specification**
Model	MGFQU- 100-22
Max. power (kW)	12.5
Max. rotating speed (rpm)	3350
Total weight	65 kg
Inertia	J= 0.0237 $kgms^2$

Kistler pressure sensor was connected to the engine cylinder whereas the angle encoder was at the crankcase. The signal was sent to Dewetron data acquisition systems which processed the signal and displayed the data. The experiment was carried out using different speed from 1000 rpm to the maximum engine speed of 2400 rpm at constant load of 3kW. Various load from 1kW to 5kW was also used for the constant speed 1600 rpm. Readings for all the tests were recorded for each of the parameters set. The data for pressure and volume against the crank angle was displayed and saved in the Dewetron data acquisition system and ready to be extracted as excel file for every ten cycles in each test. Eight different fuel blends were used and the same procedure was then repeated.

Figure 2: Dewetron data acquisition systems

Data set of the in-cylinder pressure, and volume with respect to crank angle were displayed and saved in Dewetron acquisition system. The rate of heat release (kJ/CA) was determined based on the relation of volume, crank angle, in-cylinder pressure and specific heat ratio. The standard specific heat ratio, $\gamma = 1.32$ for diesel cycle was used. The heat release rate for the constant load and varying load was analysed. The heat release rate for the constant speed and varying load was also calculated. The raw data from sensor was extracted from Dewetron and further calculation was performed using excel spread sheet.

Results and Discussion

Engine performance

Engine performance which includes brake power (kW), brake specific fuel consumption (kg/kWh), brake thermal efficiency (%) and combustion characteristics such as the-in-cylinder pressure and heat release rate (kJ/CA) for all the different types of diesel and biodiesel fuel blends was analysed.

Brake power

Figure 3 illustrates the graph of brake power for various fuel blends at different speed with a constant load of 3kW. The brake power increased with higher engine speed. High engine speed generated more heat due to the frictional force between the piston and the wall. The brake power of biodiesel was higher compared to diesel. PB10 had the highest brake power which was 4.851 at maximum speed of 2400 rpm. The brake power was reduced for PB30 by 2.12% due to lower heating value which released less energy during combustion. The graph also shows that putting additives in diesel and biodiesel slightly reduced brake power. This resulted in the highest amount of biofuel (PB30) with additives generating higher brake power. Brake power is commonly reduced due to the fact that calorific value of fuel reduces with the additives [8]. Low calorific value resulted in the fuel combustion producing less energy. At high engine speed, the engine piston moves very fast with high rotation. This means higher amount of work can be done because of the higher number of cycle.

Brake power for various change in load for different fuel mixtures is shown for constant engine speed at 1200 rpm. The brake power is illustrated in Figure 4 to indicate that the brake power increased along with the increasing load applied to the engine. This is because the load applied to the shaft required higher engine power to rotate the shaft. At higher load, the shaft rotation will be faster and this led to a higher brake power. Higher load also causes more fuel to burn which increases the heat produced in the cylinder wall. The addition of biodiesel in diesel slightly increases the brake power but the amount of biodiesel has no significant effect. As shown in the graph, putting additive in diesel and biodiesel increases the brake power at high load with the biggest difference for PB30 with 5%. This indicates that additives works well with higher biodiesel blends such as PB30.

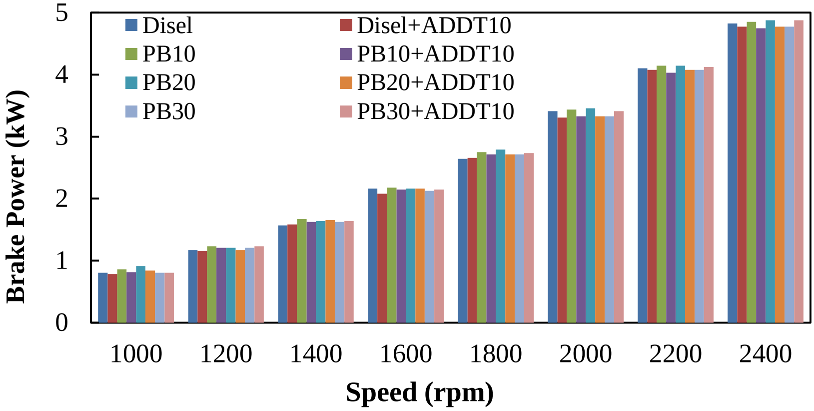

Figure 3: Brake power for different speed at constant load 3 kW

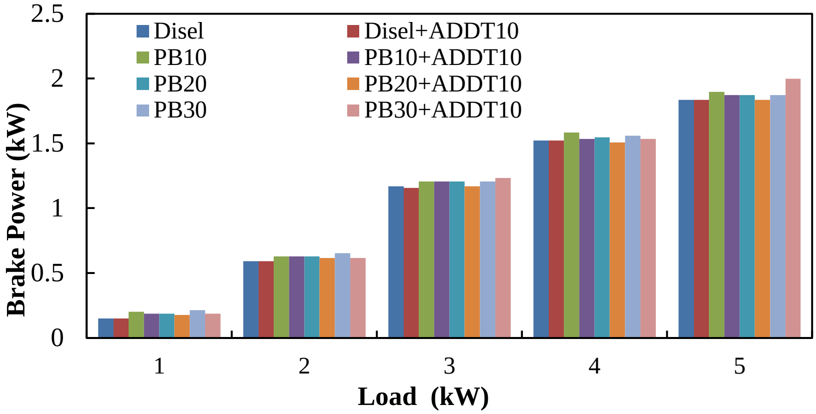

Figure 4: Brake power for various load from 1kW to 5kW at 1200 rpm

Brake thermal efficiency

Brake thermal efficiency (BTE) is the percentage of energy content from a given amount of fuel which is converted into output energy at the engine shaft. Some of the energy is lost as heat released to the surroundings due to friction between the piston and cylinder wall. Higher BTE shows better efficiency of energy conversion into useful energy output in the engine. Higher rate of combustion for a given volume of fuel will result in higher BTE.

$$\text{BTE}\ (\%) = \frac{\text{Brake Power (kW)}}{\text{Mass flow rate of fuel}\left(\frac{\text{kg}}{\text{s}}\right) \times \text{Calorific value}\ \left(\frac{\text{kJ}}{\text{kg}}\right)} \times 100 \qquad (1)$$

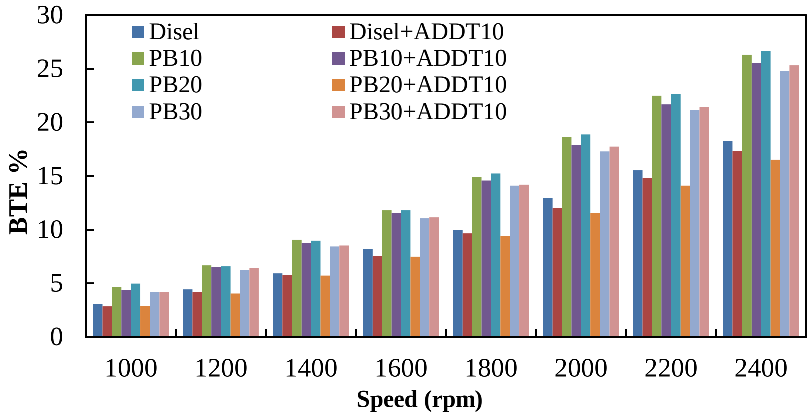

Figure 5: BTE for different speed for various type of fuel blends

Figure 5 shows the variation of BTE values for various engine speed at constant load of 3kW. Higher speed causes the BTE to increase due to the high heat generated at high rotation. The graph also shows that PB20 produced the highest BTE at all speed. This is because the high viscosity and low heating value of biodiesel slightly reduced thermal efficiency during fuel atomization. Besides, putting booster additives reduces BTE for all fuel types especially for PB20 with the significant difference around 60%. However, PB30 slightly increased the BTE due to the additional heat released from the engine because of friction. This stems from low heating value of the mixture that reduces the heat released and reduces BTE.

The BTE for various load applied to the engine from 1 kW to 5 kw is shown in Figure 6. At higher load, the graph indicates that the BTE increases for all mixtures. Higher load applied to the engine causes more fuel to burn in order to meet the high energy demand at the shaft. More composition of fuel burnt will generate more heat. Therefore, addition of biodiesel with lowest percentage (PB10) registered higher BTE compared to the other higher biodiesel percentage, compared to diesel fuel. This is due to the high energy required, thus leading to high heat released. Due to the low heating value of mixture, BTE of the mixture also decreased. This proves that adding small amount of biodiesel in the mixture efficiently increases the BTE of the engine. In addition, putting additives in each fuel mixture leads to lower BTE with very significant difference at higher loads. This is due to the low heating value of the additives requiring more heat to be released.

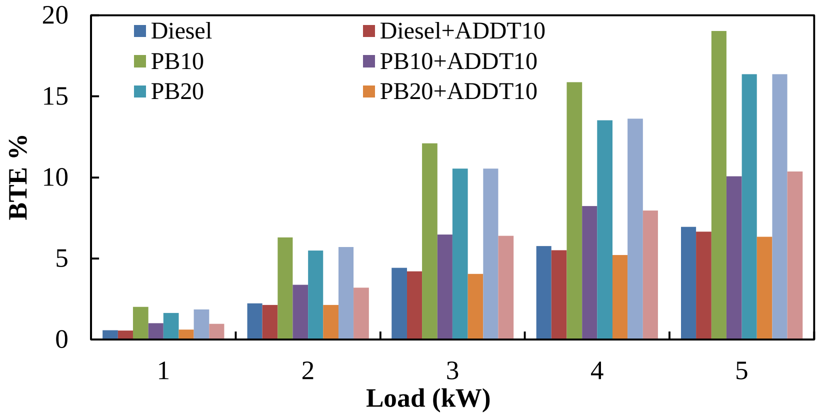

Figure 6: The BTE of fuel blend at constant speed of 1200 rpm and varying load

Brake specific fuel consumption

Brake specific fuel consumption (BSFC) is the amount of fuel needed to produce per unit of energy at the engine shaft (kg/kWh). BSFC which is higher indicates poor fuel consumption as more amount of fuel is used. Lower BSFC is better for economic fuel consumption of engine.

$$\mathrm{BSFC}\ \left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right)=\frac{\text{mass flow rate fuel}\ \left(\frac{\mathrm{kg}}{\mathrm{hr}}\right)}{\text{brake power}\ \ (\mathrm{kW})} \tag{2}$$

Figure 7 shows the BSFC for different engine speed at constant load of 3 kW. BSFC increases as the engine speed rises from 1000 rpm to maximum 2400 rpm. Higher engine speed cuts the time for combustion inside the cylinder for every cycle. Thus, the percentage of fuel from the given injected amount burnt is lower at shorter period. Overall, BSFC of biodiesel is higher compared to diesel. Biodiesel has lower calorific value and high viscosity. Thus, high amount of biodiesel is needed to produce that specified amount of energy [9] and the droplets of fuel is also bigger due to poor atomization. Adding booster causes the BSFC to reduce only for the PB30 because the amount of booster (which is 10 drops) added is only essential for the 30% palm oil and 70% diesel blend. For the other blends, the booster amount may need to be increased. This is because booster is able to reduce viscosity and improve combustion rate.

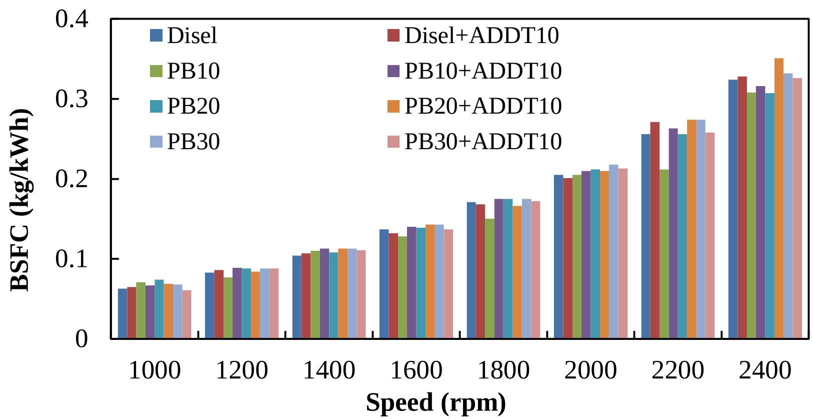

Figure 7: BSFC for various speed at 3 kW load

The BSFC of various engine load for constant engine speed of 1200 rpm is shown in Figure 8. The BSFC rises when the engine load increases. Higher engine loads burn high amount of fuel thus producing more heat which is released to the surroundings. The loss of energy has to be replaced since the engine requires more fuel. The ignition power during compression stroke which is not essential to burn the large fuel amount will also lower the rate of fuel burnt [10].

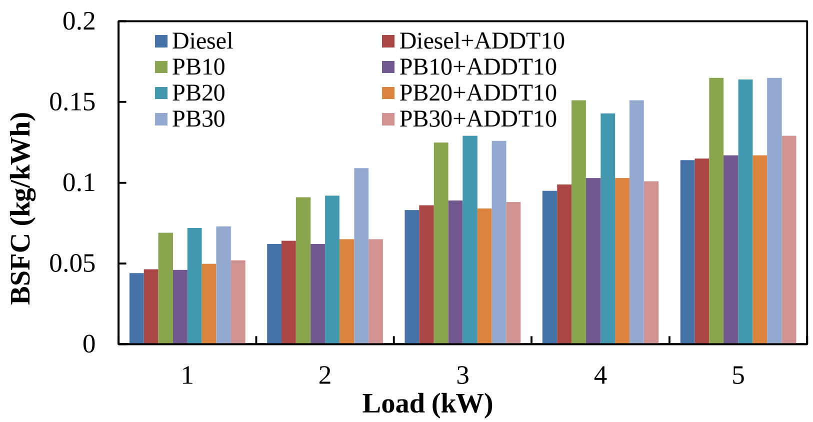

Figure 8: BSFC for various load at 1200 rpm

Combustion Characteristics

In-cylinder pressure and heat release rate

Calculation for the Heat Release Rate (HRR) is shown in Equation 3.

$$\frac{dQ}{d\theta} = P\frac{\gamma}{\gamma-1}\frac{dV}{d\theta} + V\frac{1}{\gamma-1}\frac{dP}{d\theta} \tag{3}$$

P is the in-cylinder pressure (Pa) for every crank angle rotation (deg) and V is the volume (m^3) of cylinder with respect to each crank angle.

The HRR and in-cylinder pressure for the engine speed of 1600 rpm and varying load of 1kW, 3kW and 5kW is shown in Figures 9, 10 and 11. The increase in load causes the pressure to slightly rise along with increased HRR. The higher amount of fuel is burnt to supply higher energy for the engine to run at higher load. Thus, the HRR is high. Based on HRR graph, the first decline indicates a drop in HRR when fuel is injected. The second peak indicates the main combustion peak where the ignition of fuel started.

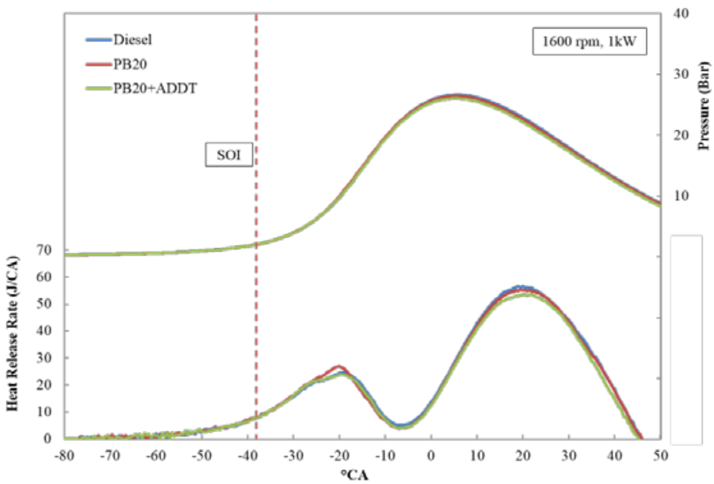

Figure 9 In-cylinder pressure and HRR for 1600rpm, 1kW

Diesel produces the highest HRR compared to other blends in all conditions. This is due to its high energy content. The graph shows thatPB20 mixture has almost similar performance to diesel. Addition of booster to the PB20 fuel led to a slight rise in HRR with the graph illustrating that PB20+ADDT has slightly higher HRR and pressure than PB20 at around 1%-2% respectively. The additive is able to reduce the viscosity of the fuel blend.

Atomization occurs easily with low viscosity fuel and complete combustion can take place. In other words, the rate of combustion for a given amount of fuel is high. More efficient combustion takes place and high energy from the fuel is generated. Booster can break the strong covalent bond between carbon atoms in fuel molecule. This contributes to lower viscosity and better fuel air reactions and increases combustibility.

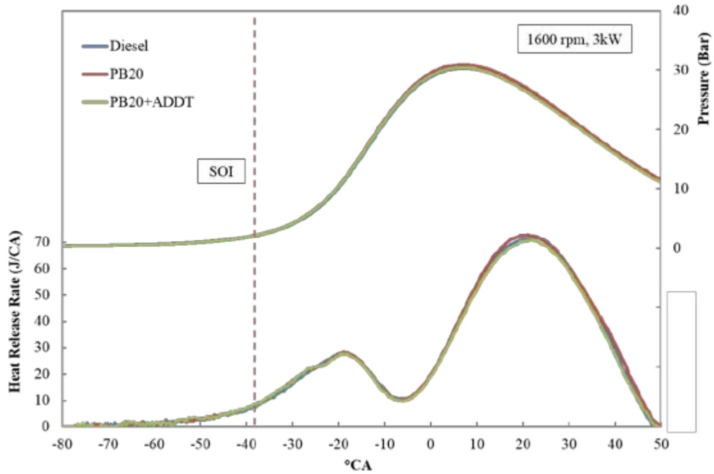

Figure 10 In-cylinder pressure and HRR for 1600 rpm, 3kW

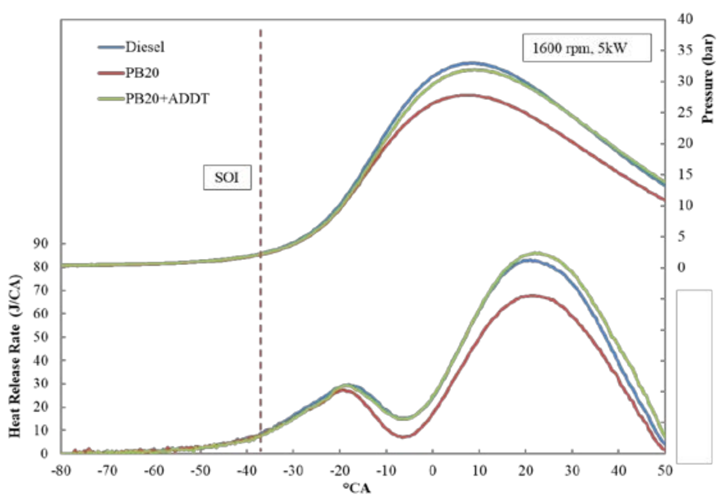

Figure 11: In-cylinder pressure and HRR for 1600 rpm, 5kW

Conclusions

Results of the experiment proved that biodiesel fuel is able to produce slightly better performance than diesel. PB10 (90% Diesel, 10% palm oil) produces optimum performance for varying load and speed. The brake power and BTE using biodiesel was 5% higher compared to diesel due to biodiesel calorific value. However, fuel consumption (BSFC) of biodiesel was higher than diesel due to the latter's high viscosity. The HRR for biodiesel with additives showed better result by generating higher HRR then diesel fuel in this experiment with 14% difference. Efficiency of biodiesel combustion for a specific injected amount of fuel was higher but the energy released was smaller compared to diesel if the same rate of combustion took place. Putting DHP additive to the fuel mixture reduced the viscosity and increased heating value of the mixture. Low viscosity of fuel led to a better fuel spray system which improved fuel atomization. The inclusion of additives slightly increased the BTE for 30% biodiesel blends and slightly reduced the BSFC to around 8% lower than diesel and biodiesel mixture due to its low viscosity. PB10 showed greater performance for low speed and low load. However, PB20 showed better performance compared to PB10. PB30, on the other hand, performed better for high speed and high load.

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