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Optimization of Injection Pressure and Injection Timing on Fuel Sprays, Engine Performances and Emissions on a Developed DI 20C Biodiesel Engine Prototype

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ABSTRACT

Biodiesel, as a renewable fuel that has the potential to replace diesel fossil fuels. With properties in the form of viscosity, density, and surface tension, which are higher than diesel fossil fuel, biodiesel produces poor spray characteristics, and also the high cetane number and oxygen content so that the ignition delay is shorter causes the start of combustion will shift more forward, therefore need to improve injection parameters including injection pressure and timing. The aim of this research is to get the optimal injection parameter optimization so as to improve engine performances and emissions. The method used is to increase the fuel injection pressure from 200 to 230 kg/cm^2 and the injection timings were retarded from 22° to 16° BTDC. The results show that increasing injection pressure can improve spray characteristics as indicated by shorter penetration and smaller spray diameter of 30% and 9.8%, respectively and increase in spray spread angle of 21.9%. Then the optimization of engine performances and emissions, obtained at an injection pressure of 230 kg/cm^2 and injection timing of 16° BTDC with an increase of power and thermal efficiency of 3.9% and 13.9%, respectively and reduction in smoke emissions of 45.2% at high load.

1. INTRODUCTION

Indonesia still relies on the use of fossil fuels. Fossil fuels are non-sustainable energy sources, which are commonly used in industrial and transportation fields. For example, diesel, dexlite, and pertadex fuels were the result of the distillation of fractions from petroleum (fossil fuels), in which the availability is limited. The use of fossil fuels also has a negative impact on the environmentally. Exhaust emissions from the combustion of fuel are one of the main causes of the greenhouse effect (such as CO, CO_2, HC, etc.). With the adverse effects of the depletion of fossil fuels, alternative fuels are needed to reduce dependence on fossil fuels.

Biodiesel is a fuel that is very potential to be used as a substitute for diesel fossil fuels and research has been conducted related to biodiesel fuels [1]. Many studies have implemented the use of biodiesel fuels in diesel engines [2-4]. This is because the raw materials derived from vegetable oils can be renewed, can be produced periodically and easily obtained. However, with properties in the form viscosity, density, and surface tension, which are higher value than diesel fossil fuels, biodiesel produces poor spray characteristics. In addition, with higher value of cetane numbers, the ignition delay is shorter, and the presence of oxygen in biodiesel [5] causes the premixed combustion process to be faster [6]. Nguyen et al. [7] investigated spray characteristics, performance, and emissions on diesel engine using biodiesel fuel. They explained that the penetration of biodiesel fuel is longer than the diesel fossil fuel. In addition, an increase in the ratio of biodiesel blends leads to an increase in spray

penetration caused by higher viscosity and spray droplet size. As a result, larger spray droplets and higher momentum. The viscosity and density of biodiesel fuels are higher so that there are longer droplets around the injector and greater momentum than diesel fuel. As a result, the spray leads to more combustion chamber walls and smaller spray angles than diesel fossil fuels.

Some researchers carried out the experimental study on the effect of injection pressure variations using biodiesel fuel. Mahanggi et al. [8] reported that an increase in injection pressure could improve these sprayed characteristics, performance, and exhaust gas emissions. Other properties, specifically cetane number, where the higher the cetane number can also result in a shorter ignition delay. A shorter ignition delay can reduce the time of mixing of fuel-air, and the starting point of flame formation is advancing, but it is certain that this time produces a more efficient performance in mixing fuel and air because the temperature and incoming air pressure become higher so that the fuel is ready to burn. Therefore, treatment is needed, which is to adjust of injection timing to get a perfect fuel atomization, combustion process so produces a performance on engines that are close to or equal to using diesel fossil fuels.

Sita and Sudarmanta [9] conducted a study of the effect of injection pressure on performance on diesel dual fuel engine. Variations are made by changing the thickness of the shim or adjusting the injector washer according to the variation, namely 190, 210, 230, and 250 kg/cm^2 with a constant engine speed of 2000 rpm and electrical loading from 200 watt to 2000 watt with intervals of 200 watt, at diesel dual fuel system

biodiesel-syngas fuels. The best performance results obtained at a pressure of 250 kg/cm^2 with an increase in the percentage of thermal efficiency of 40.77% and spray angle (α) of 29.41%, and a decrease in the percentage of SFC and spray length (L) of 13.24% and 19.23%, respectively.

Mutyalu et al. [10] investigated the effect of fuel injection pressure on the performance and emissions characteristics of a diesel engine with shea olein biodiesel fuel. The experiment was carried out on stationary water-cooled naturally aspirated single-cylinder four-stroke and direct injection diesel engine at a constant rated speed of 1500 rpm and load at 2.79 kW. The test was conducted at different injection pressures (190, 200, 210, 220, 230 bar). The best performance and emissions are produced at an injection pressure of 210 bar. Where the results of chart trends such as SFC have decreased at an injection pressure of 210 bar. While at higher injection pressures, SFC has increased because of higher momentum of fuel got impinges on cylinder walls leads to wastage of fuel and improver combustion. HC and CO emissions also decrease at an injection pressure of 210 bar.

Some researchers carried out the experimental study on the effect of injection timing variations using biodiesel fuels. Mendonca et al. [11] conducted a study on the influence of injection timing on performance and emission characteristics of simarouba biodiesel engine. The experimental aims at determining appropriate proportions of biodiesel and diesel fossil fuel for which higher efficiency is obtainable. Standard injection timing is 20.5° BTDC, and then variations are carried out by advancing and retarding injection timing to be 25.5° and 15.1° BTDC. For B20 fuel, the best performance results obtained at the timing of retarding 15.1° BTDC with improvement in brake thermal efficiency and brake specific fuel consumption. While advancing injection timing 25.5° BTDC, resulting in reduced performance compared to the standard injection timing.

Hirkude et al. [12] where this study aims to determine the effects of compression ratio and injection parameters such as injection pressure and injection timing of performance and emissions in a diesel engine. This research was conducted using different compression ratios, namely 16, 17, 18, and 19, and variations in injection parameters such as injection timing, namely 24°, 27°, and 30° BTDC, and an injection pressure of 200, 225, 250 bar. The best performance results were obtained at the compression ratio of 18 and injection pressure of 250 bar, and standard injection timing 27° BTDC. If advancing injection timing, the percentage increase of 2.01%, while the retarding injection timing increase of 6%. At injection pressure of 250 bar, the advancing of injection timing from 27° to 30° BTDC reduced smoke opacity by 3.03%. While retarding injection timing by 27° to 24° BTDC increased smoke opacity by 3.34%.

Based on previous research that the use of biodiesel fuel with its properties, requires setting injection pressure and injection timing. Thus, this study aims to improve fuel sprays, engine performances and emissions through optimization of injection pressure and injection timing on a developed DI 20C biodiesel engine prototype with crude palm oil (CPO) biodiesel fuel at low, medium, and high engine loads.

The design of a developed DI 20C biodiesel engine prototype is accorded to the characteristics of biodiesel fuels and operational condition parameters including injection pressure, injection timing, multi stage injection, and forced air combustion. This research has been carried out optimization of injection pressure and injection timing on a developed DI

20C biodiesel engine using CPO biodiesel fuel. The results of this research are fuel sprays, engine performances, emissions and engine operating temperatures can be improved.

2. EXPERIMENTAL SETUP

2.1 Fuel properties

The biodiesel used in this test was biodiesel (B100) from crude palm oil (CPO) obtained from PT. Wilmar Nabati Indonesia, where biodiesel in Indonesia uses more raw materials from palm oil because it is easily obtained [13]. But when compared to diesel fossil fuels, the properties of biodiesel fuels have a higher value of viscosity, density, surface tension, and cetane number but low at the heating value. Table 1 shows differences in the properties of diesel fossil and CPO biodiesel fuels.

Table 1. The comparison of fuel properties

Properties	Diesel fossil	Biodiesel
Lower caloric value [kJ/kg]	46218.09	42542.54
Density at 15°C [kg/m^3]	857	875
Density at 40°C [kg/m^3]	844	857
Kinematics viscosity at 40°C [mm^2/s]	4.2	4.5
Surface tension [dyne/cm]	66	68
Cetane number	53	58

2.2 Engine test

The engine used is designed specifically using biodiesel fuels. The specifications of a developed DI 20C biodiesel engine prototype is shown in Table 2.

Table 2. The specifications of engine test

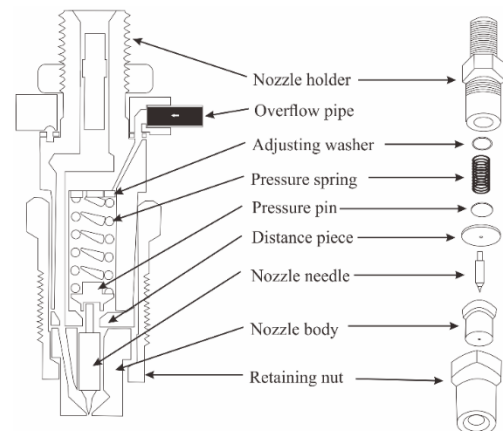| Engine specifications	Description
Merk	diamond
Model	DI 20C
Engine type	four-stroke, horizontal, water cooled
Fuel injection system	direct injection
Start of injection [°BTDC]	20
Compression ratio	16:1
Bore [mm]	105
Stroke [mm]	115
Cylinder volume [cc]	1000

2.3 Spray characteristics test

Figure 1. Detail injector geometry

To find out the results of fuel atomization, spray characteristic tests were carried out using a Bosch pump tester with biodiesel fuel. Figure 1 shows the injector used in a developed DI 20C biodiesel engine prototype. Then the injection pressure variation is performed by setting the rotation in adjusting screw on the injector until the injection pressure will be tested, where injection pressure will be seen in the pressure gauge. The pressure variations in this study were 200, 210, 220, and 230 kg/cm^2.

This test was carried out at the combustion and energy system laboratory of the mechanical engineering department, ITS Surabaya. Figure 2 shows the fuel spray characteristic test series. After testing, the length of penetration and spray angle of the fuel will be measured, and the calculation of the average droplet size (*SMD*) with the formula approach from Lefebvre [14] is as follows:

$$\text{SMD}=2.25\sigma^{0.25}\mu_L{}^{0.25}\dot{m}_L{}^{0.25}\Delta P_L{}^{-0.5}\rho_L{}^{-0.25} \qquad (1)$$

2.4 Experimental procedures

The study was carried out experimentally on a diesel engine with a constant speed of 2000 rpm. This test is carried out on a developed DI 20C biodiesel engine prototype with the main shaft that has been coupled directly with the electrical generator as an electrical dynamometer. Data retrieval was carried out on each variation of load-tested, which is 1000 watt (low load), 4000 watt (medium load), and 7000 watts (high load) with an increment of 3000 watts.

All measuring equipment has been installed in accordance with the research scheme as shown in Figure 4. Fuel buratte meter is used to measure fuel consumption. Digital manometer is used to measure air flow rates. Ampere and voltmeter are used to measure current and voltage to get the value of engine performance. Smoke tester is used to measure smoke emission.

A thermometer is used to measure the operational temperature of the engine.

The first test was to the optimization of the injection pressure on a developed DI 20C biodiesel engine prototype. Injection pressure is varied by adding an adjusting washer to the injector, as shown in Figure 1. Each additional 0.1 mm of adjusting washer thickness increases injection pressure by 10 kg/cm^2 and then spray testing was carried out, as shown in Figure 2. After the spray test is carried out, then the engine performance and emissions are tested in the engine with a predetermined injection pressure variation.

Then the second test was to the optimization of the injection timing. Variation injection timing was done by adding and reducing the thickness of the shim at the fuel injector pump, as in Figure 3. Adding thickness to the shim plate means retarding the injection timing, while reducing the thickness of the plate shim means advancing the injection timing. With a reduction or addition of 0.1 mm to the thickness of the shim plate can change the injection timing of 1° BTDC.

The parameters of the research on a developed DI 20C biodiesel engine prototype can be explained in Table 3 below:

Table 3. Test parameters on a developed DI 20C biodiesel engine prototype

Speed [rpm]	Load	Injection pressure [kg/cm^2]	Injection timing [°BTDC]
2000	low, medium, high	200, 210, 220, 230	20
2000	low, medium, high	230	16, 18, 20, 22

The testing scheme on a developed DI 20C biodiesel engine prototype is shown in Figure 4.

Notes:
1. Black screen
2. Injector nozzle
3. Injector pipeline
4. Body
5. Pressure gauge
6. Shut off valve
7. Filter
8. Fuel tank
9. Light
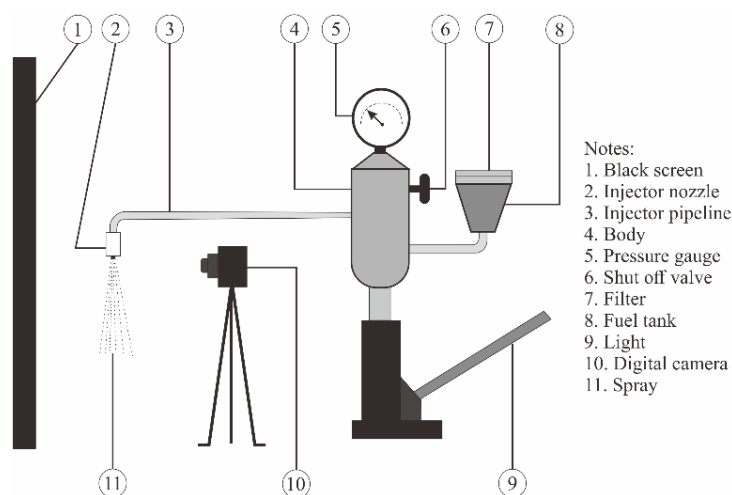10. Digital camera
11. Spray

Figure 2. Schematic of spray characteristic testing

Figure 3. Setting the injection timing at the injection pump by adding a shim plate
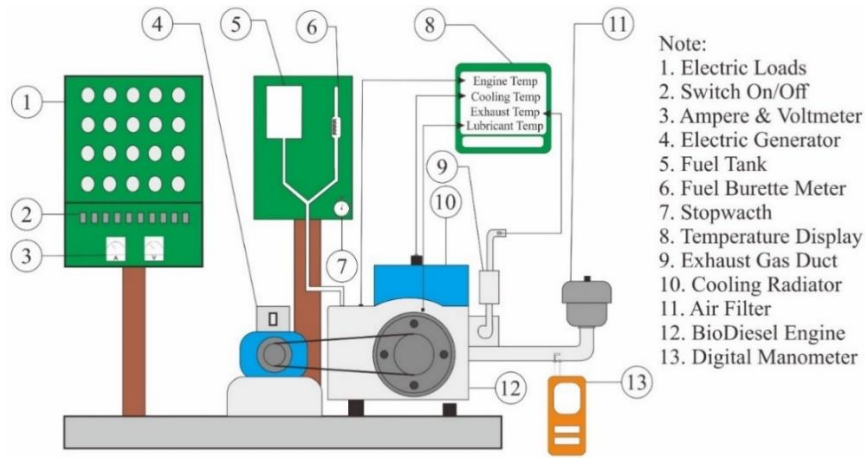
Figure 4. Schematic of the engine performance test
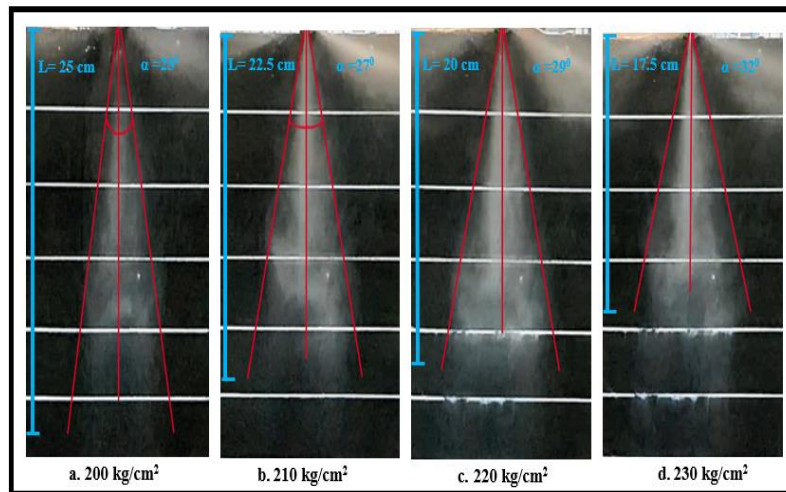

Figure 5. The visualization of sprays characteristics of biodiesel fuels

3. RESULTS AND DISCUSSION

The analysis of this study was carried out by compiling the results of the spray characteristics and experimental results of the performance test and exhaust emission test.

3.1 Result of spray injection characteristics test

Based on the properties of biodiesel that we have acknowledged, in the previous paragraph. Higher viscosity causes higher flow momentum so that the spray penetration length becomes longer, while higher surface tension makes it difficult for droplets of fuel to become smaller granules (secondary break up), which will then spread in all directions. This spread causes the contact surface of droplet fuel with less air, so the evaporation that occurs will be longer than the fuel, which has a higher surface tension value.

Figure 5 shows a visualization of the characteristics of the fuel sprays with different injection pressures. Under standard fuel injection pressure conditions of 200 kg/cm^2, the spray penetration length is 25 cm, and the spray spread angle is 25°. Then by increasing injection pressure, the spray penetration length decreases and the spray spread angle is increased so as to produce more atomization good. Optimal injection pressure is obtained of 230 kg/cm^2, which is characterized by a 30% reduction in spray penetration length. This causes the flow momentum to be shorter thereby reducing fuel buildup in the

combustion chamber wall. While the spray spread angle increased by 21.9%, causing an increase in the contact surface of the fuel droplet with the combustion air. This causes more mixing, evaporation and atomization of the fuel so that the combustion process becomes more perfect.

The increased of injection pressure is due to the addition of the thickness of the injector washer. Table 4 shows the results of Sauter Mean Diameter (*SMD*) calculations for all loads using Eq. (1).

Table 4. The results of Sauter mean diameter (*SMD*) calculations at all loads

Electrical load	SMD (μm)			
	Injection pressure [kg/cm^2]			
	200	**210**	**220**	**230**
Low	0.0138	0.0133	0.0130	0.0125
Medium	0.0148	0.0144	0.0139	0.0134
High	0.0161	0.0156	0.0150	0.0144

The calculation of the *SMD* equation explains that increasing injection pressure can reduce the *SMD* value at all engine loads, where the lowest *SMD* value is obtained at an injection pressure of 230 kg/cm^2.

The percentage decrease in *SMD* at low, medium and high loads were 9.4%, 9.5%, and 10.6% of the standard injection pressure, respectively. This shows that the addition of

injection pressure will accelerate the spray evolution process, which is characterized by a smaller *SMD* value which will result in more active and faster atomization. Droplets break up more quickly into smaller secondary droplets, making it easier for evaporation and mixing with combustion air. This will initiate the formation of a homogeneous mixture and encourage a greater ignition process as explained by previous studies [15]. Mahanggi et al. [8] explained that increasing the fuel injection pressure resulted in better spray atomization and a larger spray angle. This improved atomization process tends to reduce the duration of the ignition delay, the duration of premixed combustion and diffusion combustion, and increase the total of heat release [6, 16].

Table 4 also shows the trend that the greater the engine load, the higher the SMD value. This is due to the increase in engine load, it requires more fuel consumption.

3.2 Effects of injection pressure

This test was carried out to determine the performance and emissions with injection pressure variations on a developed DI 20C biodiesel engine prototype using CPO biodiesel (B100) fuel at low, medium, and high loads. The final results of this study were performance and exhaust emissions, including power, brake thermal efficiency (BTE), specific fuel consumption (SFC), air-fuel ratio, and smoke opacity, then also displayed temperatures including the engine body, lubricants, cooling water and exhaust gases.

Figure 6 shows that the performance of a developed DI 20C biodiesel engine prototype using diesel fossil fuels was better than using biodiesel fuels at all loads. It can be seen from the power, and thermal efficiency values were higher and lower SFC values from using biodiesel fuel. This is because CPO biodiesel fuel has a low calorific value so that the amount of fuel consumed is large, so the mixture becomes richer compared to diesel fossil fuel, and also high viscosity, density, and surface tension are the reason for the decline in engine performance using biodiesel fuel [17, 18].
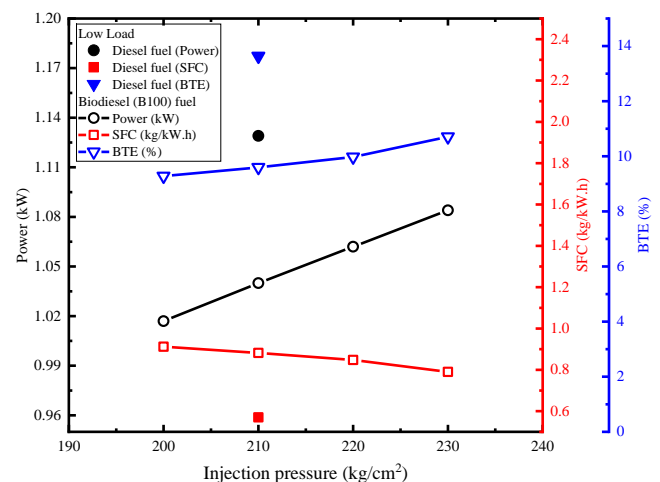
Figure 6 also explains the effect of injection pressure on power, specific fuel consumption (SFC), and thermal efficiency (BTE) at all engine loads. All engine loads show that the trendline graphs for each parameter were more likely to be the same with the variation of injection pressure. With increasing injection pressure improves power, BTE values, and lowering SFC value at all engine loads with an optimal injection pressure of 230 kg/cm^2.

The low load, the maximum power value reaches 1.084 kW with a percentage increase of 6.2%, the minimum specific fuel consumption value reaches 0.79 kg/kW.h with a percentage decrease of 13.3%, and then the thermal efficiency value reaches 10.7% with a percentage increase of 13.4% from standard injection pressure as shown in Figure 6a. The medium load, the maximum power value reaches 3.673 kW with a percentage increase of 1.2%, the minimum specific fuel consumption value reaches 0.326 kg/kW.h with a percentage decrease of 12.12%, and then the thermal efficiency value reaches 25.9% with a percentage increase of 12.15% from standard injection pressure as shown in Figure 6b. The high load, the maximum power value reaches 6.55 kW with a percentage increase of 1%, the minimum specific fuel consumption value reaches 0.255 kg/kW.h with a percentage decrease of 16.4%, and then the thermal efficiency value reaches 33.2% with a percentage increase of 18.1% from standard injection pressure as shown in Figure 6c. This is due

to the shorter flow momentum, which reduces fuel buildup on the piston crown and a greater spread of fuel spray so that it is distributed to all combustion chambers and allows the material to mix with more air.

Then also the spray evolution process is faster due to better atomization so that the process of fuel evaporation is improved, and the mixing of fuel and air is more homogeneous, as seen in the visualization of Figure 3. This will increase engine power, which has an effect on increasing thermal efficiency, as explained in previous studies [19]. The specific fuel consumption value of a developed DI 20C biodiesel engine prototype using biodiesel fuel is higher than diesel fossil fuel, and this is because the density value of biodiesel fuel is higher, as explained in previous studies [3, 18]. The addition of injection pressure affects the decrease in the value of SFC. This is due to an increase in engine power so that the engine is more efficient in consuming fuel.

Figure 7 shows the air-fuel ratio and smoke emissions in a developed DI 20C biodiesel engine prototype using diesel fossil fuels higher than using biodiesel fuels, while the exhaust gas temperature is lower at all loads. The reduction in an air-fuel ratio in engines using biodiesel fuel was caused by the amount of fuel used more because of the lower calorific value. The reduction in smoke emissions due to biodiesel fuels has a lower carbon value than fossil fuels. Increased exhaust gas temperature using biodiesel fuel due to the amount of oxygen content, which is more so that it increases the combustion process [3, 17].

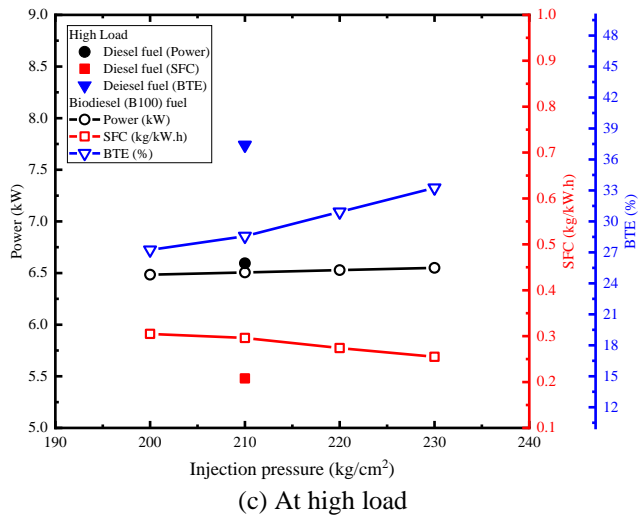(a) At low load
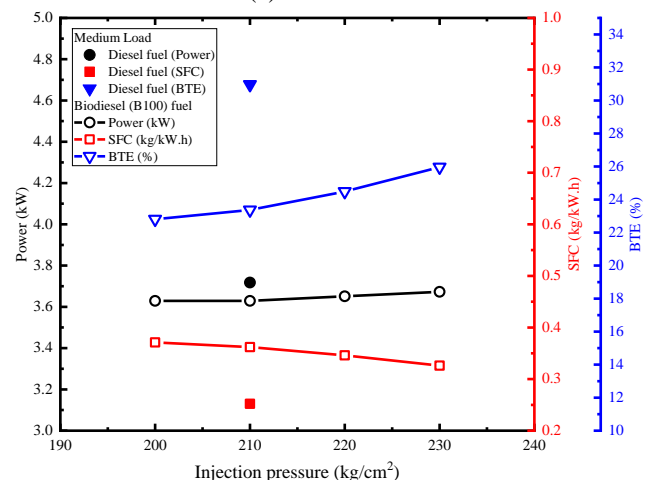
(b) At medium load

(c) At high load

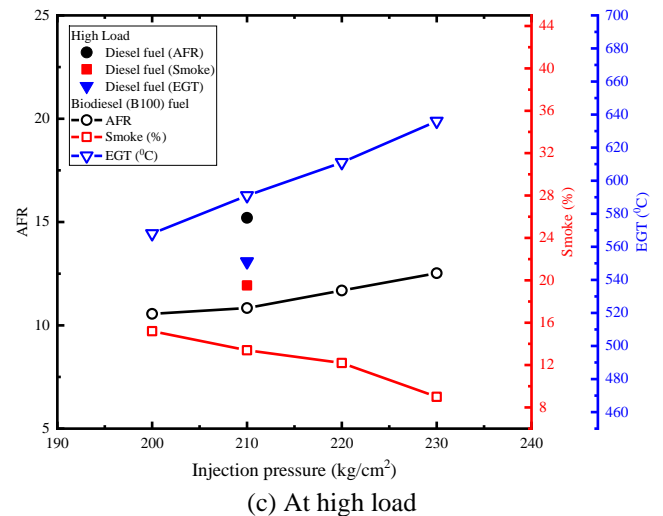**Figure 6.** Effect of injection pressure on power, SFC and BTE

Figure 7 also shows that the effect of injection pressure on the air-fuel ratio (AFR), smoke emissions, and exhaust gas temperatures at all loads. All engine loads show that the trendline graphs for each parameter were more likely to be the same with a variation of injection pressure. Increasing the injection pressure is an optimal value of 230 kg/cm^2 can improve the value of the air-fuel ratio, smoke emissions, and exhaust gas temperatures on a developed DI 20C biodiesel engine prototype using biodiesel fuel at all loads.

(a) At low load

(b) At medium load

(c) At high load

Figure 7. Effect of injection pressure on AFR, smoke emission, and EGT
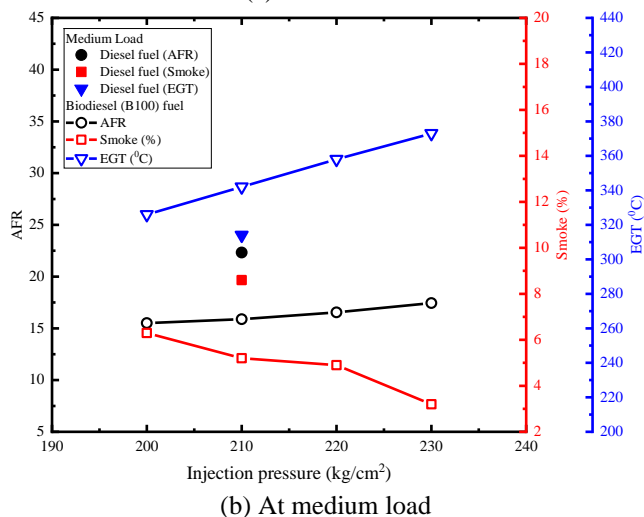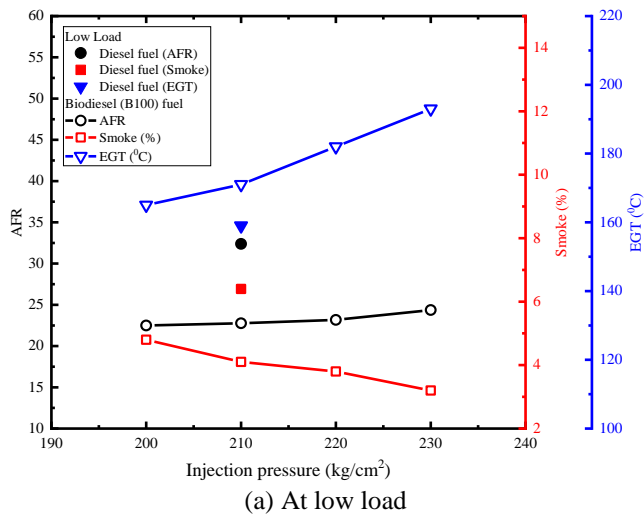
The low load, the maximum air-fuel ratio value reaches 24.3 with a percentage increase of 7.7%, the minimum smoke emission value reaches 3.2% with a percentage decrease of 33.3%, and then the maximum exhaust gas temperature value reaches 193°C with a percentage increase of 14.5% from standard injection pressure as shown in Figure 7a. The medium load, the maximum air-fuel ratio value reaches 17.4 with a percentage increase of 11.1%, the minimum smoke emission value reaches 3.2% with a percentage decrease of 49.2%, and then the maximum exhaust gas temperature value reaches 373°C with a percentage increase of 12.6% from standard injection pressure as shown in Figure 7b. The high load, the maximum air-fuel ratio value reaches 12.5 with a percentage increase of 15.7%, the minimum smoke emission value reaches 9% with a percentage decrease of 40.7%, and then the maximum exhaust gas temperature value reaches 636°C with a percentage increase of 10.7% from standard injection pressure as shown in Figure 7c.

The increase in an air-fuel ratio by increasing injection pressure is caused by a decrease in SFC value due to better atomization [20]. The reduction in smoke emissions by increasing the injection pressure using biodiesel fuel is caused by an increase in atomization and evaporation and also a higher amount of oxygen so that combustion is better [19]. The increase in exhaust gas temperature by increasing the injection pressure using biodiesel fuel is due to better atomization so that the mixing of fuel and air is more homogeneous and produces maximum combustion, which resulting in an increase in combustion temperature.

Figure 8 shows the difference in temperature in a developed DI 20C biodiesel engine prototype between using diesel fossil fuels and biodiesel fuels. This temperature consists of engine body temperature, lubricant temperature, and cooling water temperature. It is seen that the value of the three temperatures using biodiesel fuel is higher than using fossil fuel at all engine loads. The increase of third temperatures is due to the amount of biodiesel fuel used more to offset the engine load. Thus, the amount of oxygen content is more so that it increases the combustion process in the combustion chamber [3, 17].

Figure 8 also shows the effect of injection pressure on engine body temperature, lubricant temperature, and cooling water temperature at all load. All engine loads show that the trendline graphs for each parameter were more likely to be the

same with a variation of injection pressure. Increasing the injection pressure is an optimal value of 230 kg/cm^2 can improve the value of the three temperatures on a developed DI 20C biodiesel engine prototype using biodiesel fuel at all loads.

(a) At low load
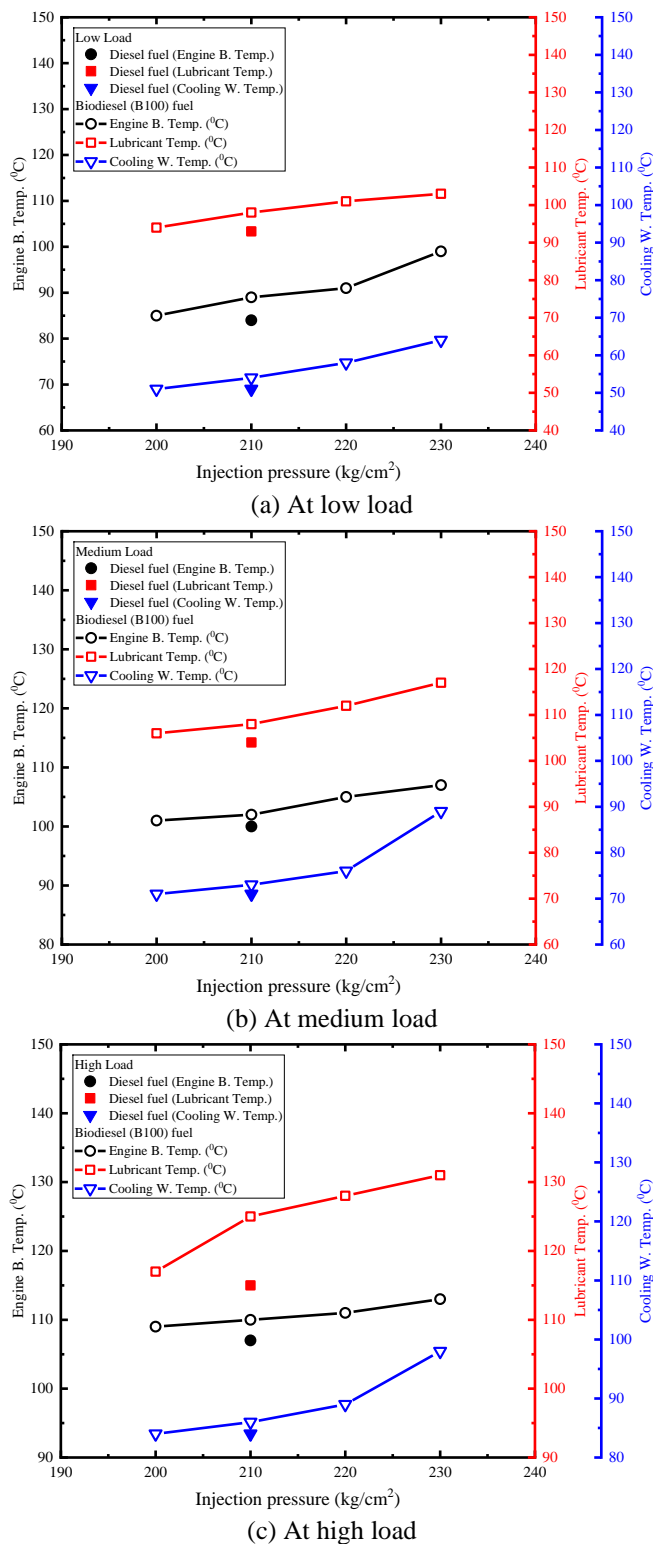

(b) At medium load

(c) At high load

Figure 8. Effect of injection pressure on engine body temperature, lubricant temperature, and cooling water temperature

The low load, maximum engine body temperature value reaches 99°C with a percentage increase of 14.1%, the maximum lubricant temperature value reaches 103°C with a percentage increase of 8.7%, and the cooling water

temperature value reaches 64°C with a percentage increase of 25.5% from standard injection pressure as shown in Figure 8a. The medium load, maximum engine body temperature value reaches 107°C with a percentage increase of 5.6%, the maximum lubricant temperature value reaches 117°C with a percentage increase of 9.4%, and the cooling water temperature value reaches 89°C with a percentage increase of 20.2% from standard injection pressure as shown in Figure 8b. The high load, maximum engine body temperature value reaches 113°C with a percentage increase of 3.5%, the maximum lubricant temperature value reaches 131°C with a percentage increase of 10.7%, and the cooling water temperature value reaches 98°C with a percentage increase of 14.3% from standard injection pressure as shown in Figure 8c. Increasing the injection pressure causes complete combustion, which influences the temperature rise because it results from better atomization so that the mixing of biodiesel fuel with air is more homogeneous. Then also evaporation from droplets is better because of the presence of more oxygen [21].

3.3 Effects of injection timing

This section discusses the effect of injection timing on engine performance, emissions, and temperature.

Figure 9 shows that the performance of a developed DI 20C biodiesel engine prototype using diesel fossil fuel was better than using biodiesel fuels at all loads. It can be seen from the power, and thermal efficiency values were higher and lower SFC values of a developed DI 20C biodiesel engine prototype using biodiesel fuel. The decrease in engine performance is influenced by the properties of the biodiesel fuel itself, such as low calorific values so that chemical energy is converted to mechanical energy is less. Biodiesel has a high density and viscosity and a high surface tension so that atomization is not good, and the evaporation of fuel is low so that the quality of the mixture between fuel and air is poorer. Besides that, biodiesel fuel has a high cetane number so that the ignition delay period is shorter and allows faster start of combustion resulting in the peak of premixed combustion being too close to the upper dead point (TDC) on the cylinder so that it affects the reduction of diffusion combustion with a longer combustion duration [18].

Figure 9 also explains the effect of injection timing on power, specific fuel consumption (SFC), and thermal efficiency (BTE) at all engine loads. All engine loads show that the trendline graphs for each parameter were more likely to be the same with a variation of injection timing. With retarded injection timing improves power, BTE values and lowering SFC value at all engine loads with an optimal injection timing of 16° BTDC.

The low load, the maximum power value reaches 1.106 kW with a percentage increase of 2.4%, the minimum specific fuel consumption value reaches 0.748 kg/kW.h with a percentage decrease of 11%, and then the thermal efficiency value reaches 11.3% with a percentage increase of 10% from the injection timing being advanced of 22° BTDC as shown in Figure 9a. The medium load, the maximum power value reaches 3.695 kW with a percentage increase of 2.3%, the minimum specific fuel consumption value reaches 0.284 kg/kW.h with a percentage decrease of 20.8%, and then the thermal efficiency value reaches 29.7% with a percentage increase of 20.7% from the injection timing being advanced of 22° BTDC as shown in Figure 9b. The high load, the maximum power value reaches 6.572 kW with a percentage increase of 3.9%, the minimum

specific fuel consumption value reaches 0.236 kg/kW.h with a percentage decrease of 13.8%, and then the thermal efficiency value reaches 35.9% with a percentage increase of 13.9% from the injection timing being advanced of 22° BTDC as shown in Figure 9c. This is because the peak of the premixed combustion moves slightly away from the TDC following the peak of the combustion premixed of diesel fossil fuel, so that the diffusion combustion is optimal, due to retarded of the injection timing. Then also, if retarded of the injection timing, then the pressure and temperature at the end of the compression stroke are higher so that the premixed combustion becomes maximum. In addition, the atomization is better because the injection pressure used is optimal at 230 kg/cm^2 at various injection timing variations. Thus, generating greater power with more efficient fuel consumption thereby increasing the value of thermal efficiency.

Figure 9 also explains the effect of injection timing on power, specific fuel consumption (SFC), and thermal efficiency (BTE) at all engine loads. All engine loads show that the trendline graphs for each parameter were more likely to be the same with a variation of injection timing. With retarded injection timing improves power, BTE values and lowering SFC value at all engine loads with an optimal injection timing of 16° BTDC.

The low load, the maximum power value reaches 1.106 kW with a percentage increase of 2.4%, the minimum specific fuel consumption value reaches 0.748 kg/kW.h with a percentage decrease of 11%, and then the thermal efficiency value reaches 11.3% with a percentage increase of 10% from the injection timing being advanced of 22° BTDC as shown in Figure 9a. The medium load, the maximum power value reaches 3.695 kW with a percentage increase of 2.3%, the minimum specific fuel consumption value reaches 0.284 kg/kW.h with a percentage decrease of 20.8%, and then the thermal efficiency value reaches 29.7% with a percentage increase of 20.7% from the injection timing being advanced of 22° BTDC as shown in Figure 9b. The high load, the maximum power value reaches 6.572 kW with a percentage increase of 3.9%, the minimum specific fuel consumption value reaches 0.236 kg/kW.h with a percentage decrease of 13.8%, and then the thermal efficiency value reaches 35.9% with a percentage increase of 13.9% from the injection timing being advanced of 22° BTDC as shown in Figure 9c. This is because the peak of the premixed combustion moves slightly away from the TDC following the peak of the combustion premixed of diesel fossil fuel, so that the diffusion combustion is optimal, due to retarded of the injection timing. Then also, if retarded of the injection timing, then the pressure and temperature at the end of the compression stroke are higher so that the premixed combustion becomes maximum. In addition, the atomization is better because the injection pressure used is optimal at 230 kg/cm^2 at various injection timing variations. Thus, generating greater power with more efficient fuel consumption thereby increasing the value of thermal efficiency.

Whereas by advancing the injection timing by 22° BTDC, resulting in a decrease in power, SFC and BTE. This is because the pressure and air temperature are still low when the injection starts [22] and causes the fuel not to burn completely and produce incomplete combustion.

Figure 10 shows the air-fuel ratio and smoke emissions in a developed DI 20C biodiesel engine prototype using diesel fossil fuels higher than using biodiesel fuels, while the exhaust gas temperature is lower at all loads. The reduction in an air-fuel ratio in engines using biodiesel fuel was caused by the

amount of fuel used more because of the lower calorific value. The reduction in smoke emissions due to biodiesel fuel has a lower carbon value than fossil fuels. The increase in the temperature of the exhaust gas by using biodiesel fuel is due to the higher oxygen content in biodiesel. The existence of this oxygen then plays an active role in the oxidation process, so as a whole can improve the combustion process [17]. Increased exhaust gas temperature using biodiesel fuel due to the amount of oxygen content, which is more so that it increases the combustion process [17].
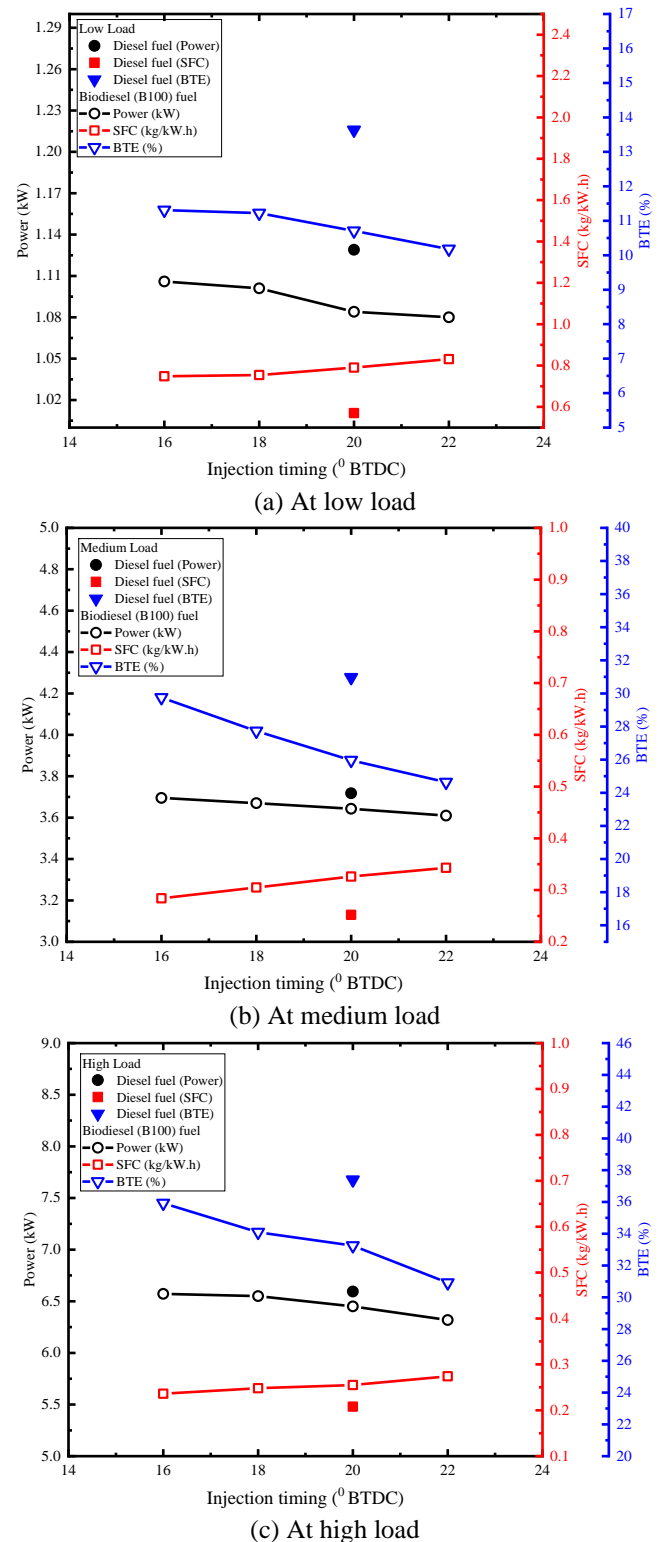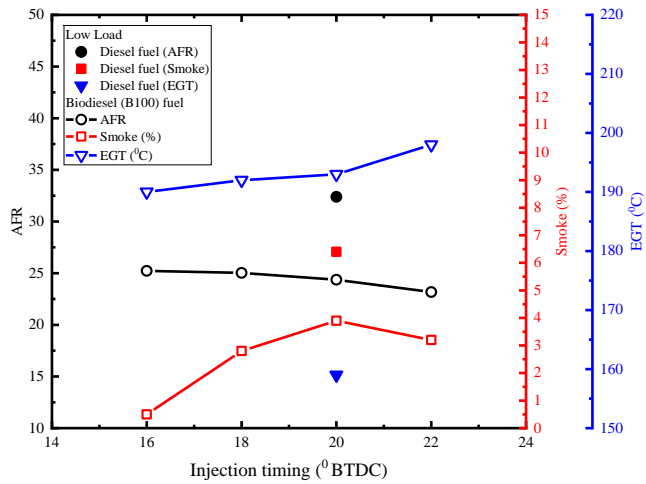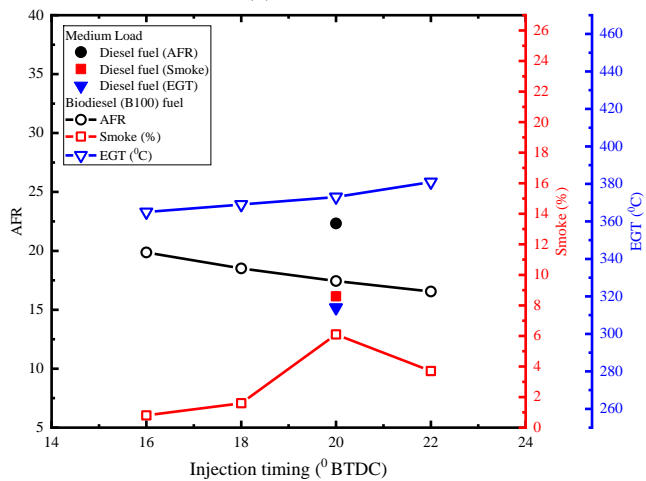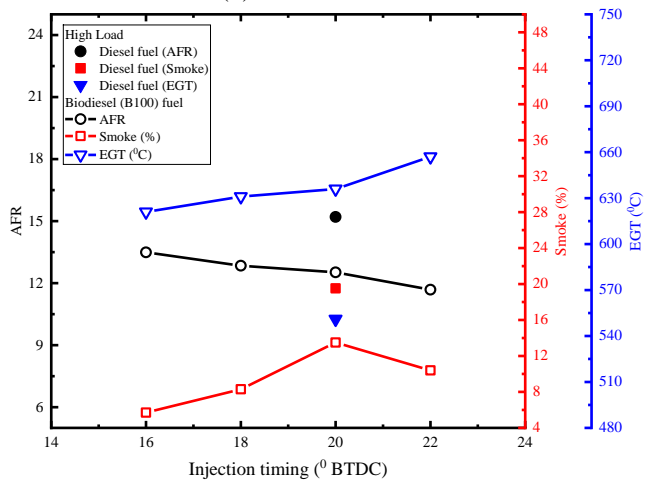

(a) At low load

(b) At medium load

(c) At high load

Figure 9. Effect of injection timing on power, SFC, and BTE

(a) At low load

(b) At medium load

(c) At high load

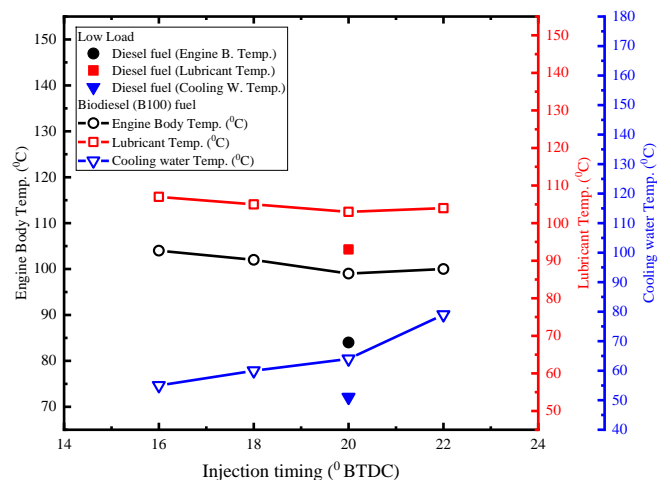**Figure 10.** Effect of injection timing on AFR, smoke emission, and EGT

Figure 10 also shows that the effect of injection timing on the air-fuel ratio (AFR), smoke emissions, and exhaust gas temperatures at all loads. All engine loads show that the trendline graphs for each parameter were more likely to be the same with a variation of injection timing. Retarded the injection timing is the optimal value of 16° BTDC can improve the value of the air-fuel ratio, smoke emissions, and exhaust gas temperatures on a developed DI 20C biodiesel engine prototype at all loads.

The low load, maximum air-fuel ratio value reaches 25.2

with a percentage increase of 8.1%, the minimum smoke emission value reaches 0.5% with a percentage decrease of 84.4%, and then minimum exhaust gas temperature value reaches 190°C with a percentage decrease of 4% from the injection timing being advanced of 22° BTDC as shown in Figure 10a. The medium load, maximum air-fuel ratio value reaches 19.9 with a percentage increase of 16.7%, the minimum smoke emission value reaches 0.8% with a percentage decrease of 78.4%, and then minimum exhaust gas temperature value reaches 365°C with a percentage decrease of 4.2% from the injection timing being advanced of 22° BTDC as shown in Figure 10b. The high load, maximum air-fuel ratio value reaches 13.5 with a percentage increase of 13.4%, the minimum smoke emission value reaches 5.7% with a percentage decrease of 45.2%, and then minimum exhaust gas temperature value reaches 621°C with a percentage decrease of 5.5% from the injection timing being advanced of 22° BTDC as shown Figure 10c.

All loads, the value of the air-fuel ratio increases by retarded the injection timing at 16° BTDC, while the value of smoke emissions and exhaust gas temperatures decreases by retarded the injection timing. This is due to the injection timing approaching TDC, and with high injection pressure, the atomization of fuel when sprayed gets better and is supported by high air pressure and temperature, resulting in low smoke opacity, EGT, and high AFR as well.

Whereas by advancing the injection timing by 22° BTDC, resulting in a decrease in air-fuel ratio and Smoke Opacity, while the value of exhaust gas temperature increases. This is because the pressure and air temperature are still low when the injection starts [22] and causes the fuel not to burn completely and produce incomplete combustion. This result shows that the most effective angle to produce maximum power is the smallest angle. It can be believed that the higher cetane number on biodiesel fuel is very influential at high combustion rates as well and resulting in low smoke emission [23]. Krishnamoorthi et al. [24] reported that advanced injection timing reduces the ignition delay and leads to the accumulation of less fuel, thus increases the smoke opacity [24]. Song et al. [25] also reported that the use of biodiesel could reduce smoke opacity. This is because biodiesel is free of sulfur and aromatic. Smoke is produced from the dehydrogenation of polycyclic from aromatic processes. In addition, the unsaturated fatty acids in biodiesel also affect the combustion process. Because unsaturated fatty acids have a saturated vapor temperature that is smaller than diesel fossil fuel, so biodiesel is more volatile, and combustion can be completely [25].
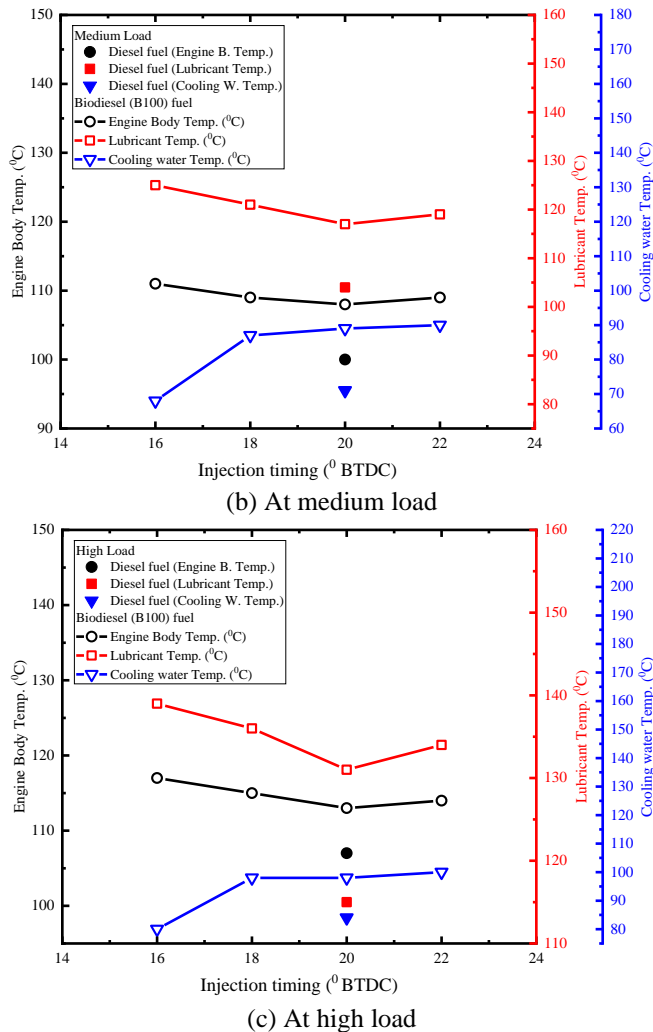

(a) At low load

(b) At medium load

(c) At high load

Figure 11. Effect of injection timing on engine body temperature, lubricant temperature, and cooling water temperature

Figure 11 shows the difference in temperature on a developed DI 20C biodiesel engine prototype between using diesel fossil fuels and biodiesel fuels. This temperature consists of engine body temperature, lubricant temperature, and cooling water temperature. It appears that the value of three temperatures using biodiesel fuel is higher than using fossil fuels at all engine loads. The increase of third temperatures is due to the mass flow rate of biodiesel fuel more than fossil fuels to offset the engine load. Thus, the amount of oxygen content is more so that it increases the combustion process in the combustion chamber [17, 18].

The low load, maximum engine body temperature value reaches 104°C with a percentage increase of 3.8%, the maximum lubricant temperature value reaches 107°C with a percentage increase of 2.8%, and the cooling water temperature value reaches 55°C with a percentage decrease of 30.4% from the injection timing being advanced of 22° BTDC as shown in Figure 11a. The medium load, maximum engine body temperature value reaches 111°C with a percentage increase of 1.8%, the maximum lubricant temperature value reaches 125°C with a percentage increase of 4.8%, and the cooling water temperature value reaches 68°C with a percentage decrease of 24.4% from the injection timing being advanced of 22° BTDC as shown in Figure 11b. The high load, maximum engine body temperature value reaches 117°C with a percentage increase of 2.6%, the maximum lubricant

temperature value reaches 139°C with a percentage increase of 3.6%, and the cooling water temperature value reaches 80°C with a percentage decrease of 20% from the injection timing being advanced of 22° BTDC as shown in Figure 11c. The increase in engine body temperature and oil temperature when retarded the injection timing due to pressure and temperature at the end of compression is too high because it is approaching the top dead center (TDC), so resulting in maximum combustion and high temperatures.

Then, with advancing injection timing too early of 22° BTDC, an increase in the three temperatures. The increase was due to better mixing of fuel and air so that premix combustion increased, and an increase in temperatures occurred.

4. CONCLUSIONS

Optimization of injection pressure and injection timing on fuel sprays, engine performances, and emissions on a developed DI 20C biodiesel engine prototype, it can be drawn several conclusions.

Fuel sprays can improve with the addition of injection pressure at the highest injection pressure of 230 kg/cm^2 with the following results:
- ➢ The length of spray penetration decreases by 30%.
- ➢ Spray spread angle increased by 21.9%.
- ➢ Sauter Mean Diameter (*SMD*) decreased by an average of 9.8%.

Optimization of injection pressure was obtained at an injection pressure of 230 kg/cm^2 with the following results:
- ➢ At low load where engine power increases by 6.2%, specific fuel consumption (SFC) decreases by 13.3%, thermal efficiency increases by 13.4%, air and fuel ratio increase by 3.2% and smoke emissions decrease by 33.3%, and exhaust gas temperatures increased by 14.5% of standard injection pressure.
- ➢ At medium load where engine power increases by 1.2%, specific fuel consumption (SFC) decreases by 12.12%, thermal efficiency increases by 12.5%, air and fuel ratio increase by 11.1% and smoke emissions decrease by 49.2%, and exhaust gas temperatures increased by 12.6% of standard injection pressure.
- ➢ At high load where engine power increases by 1%, specific fuel consumption (SFC) decreases by 16.4%, thermal efficiency increases by 18.1%, air and fuel ratio increase by 15.7% and smoke emissions decrease by 40.7%, and exhaust gas temperatures increased by 10.7% of standard injection pressure.

Optimization of injection timing at injection pressure 230 kg/cm^2 obtained optimal injection timing of 16° BTDC with the following results:
- ➢ At low load where engine power increases by 2.4%, specific fuel consumption (SFC) decreases by 11%, thermal efficiency increases by 10%, air and fuel ratio increase by 8.1% and smoke emissions decrease by 84.4% and exhaust gas temperatures decreased by 4% of the injection timing with the highest value.
- ➢ At medium load where engine power increases by 2.3%, specific fuel consumption (SFC) decreases by 20.8%, thermal efficiency increases by 20.7%, air and fuel ratio increase by 16.7% and smoke

emissions decrease by 78.4% and exhaust gas temperatures decreased by 4.2% of the injection timing with the highest value.

➢ At high load where engine power increases by 3.9%, specific fuel consumption (SFC) decreases by 13.9%, thermal efficiency increases by 13.9%, air and fuel ratio increase by 13.4% and smoke emissions decrease by 45.2% and exhaust gas temperatures increased by 5.5% of the injection timing with the highest value.

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NOMENCLATURE

SMD	sauter mean diameter, μm
ΔP	atomizer pressure drop, kg/cm^2
$\dot{m}$	mass flow of sprayed liquid, kg/s
L	spray length, mm

Greek symbols

σ	surface tension, kg/s^2
μ	dynamic viscosity, kg/m.s
ρ	liquid density, kg/m^3
α	spray angle, ^{0}

Subscripts

L	characteristic dimension

Abbreviations

BTDC	before top dead center
SFC	specific fuel consumption
AFR	air fuel ratio
CPO	crude palm oil
LHV	lower heating value
BTE	brake thermal efficiency
EGT	exhaust gas temperature
CA	crank angle
HC	Hydrocarbon
SOC	start of combustions
CO	carbon monoxide
CO_2	carbon dioxide