Article

Influence of Fuel Injection Pressure on the Emissions Characteristics and Engine Performance in a CRDI Diesel Engine Fueled with Palm Biodiesel Blends

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Abstract: This experiment investigates the combustion and emissions characteristics of a common rail direct injection (CRDI) diesel engine using various blends of pure diesel fuel and palm biodiesel. Fuel injection pressures of 45 and 65 MPa were investigated under engine loads of 50 and 100 Nm. The fuels studied herein were pure diesel fuel 100 vol.% with 0 vol.% of palm biodiesel (PBD0), pure diesel fuel 80 vol.% blended with 20 vol.% of palm biodiesel (PBD20), and pure diesel fuel 50 vol.% blended with 50 vol.% of palm biodiesel (PBD50). As the fuel injection pressure increased from 45 to 65 MPa under all engine loads, the combustion pressure and heat release rate also increased. The indicated mean effective pressure (IMEP) increased with an increase of the fuel injection pressure. In addition, for 50 Nm of the engine load, an increase to the fuel injection pressure resulted in a reduction of the brake specific fuel consumption (BSFC) by an average of 2.43%. In comparison, for an engine load of 100 Nm, an increase in the fuel injection pressure decreased BSFC by an average of 0.8%. Hydrocarbon (HC) and particulate matter (PM) decreased as fuel pressure increased, independent of the engine load. Increasing fuel injection pressure for 50 Nm engine load using PBD0, PBD20 and PBD50 decreased carbon monoxide (CO) emissions. When the fuel injection pressure was increased from 45 MPa to 65 MPa, oxides of nitrogen (NOx) emissions were increased for both engine loads. For a given fuel injection pressure, NOx emissions increased slightly as the biodiesel content in the fuel blend increased.

Keywords: combustion pressure; engine performance; fuel injection pressure; palm biodiesel; exhaust emissions

1. Introduction

Modern countries consume a lot of energy due to rapid population growth and complex and diverse industrial development. Thus, many countries are consuming more and more energy based on fossil fuels. The use of fossil fuels is known to cause problems such as global warming, climate change, pollution of the atmospheric environment and depletion of fossil fuels [1]. Additionally, such usage can be detrimental to human health. Among the emissions from diesel engines, known as exhaust gas, that harm humans are hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) and oxides of nitrogen (NOx) [2]. For this reason, many researchers are working to study the use of biodiesel fuels [3–5]. Biodiesel oil is known as an alternative fuel for diesel engines. The beneficial characteristics of biodiesel fuels are high biodegradability, high cetane number, better inherent lubricity, renewability, sustainability, environmental friendliness, superior flash point and non-toxicity [6]. Further, biodiesel has minimal aromatic hydrocarbon and sulfur content. The biodiesel structure contains about 10–12% oxygen by weight. In addition, biodiesel oils can be used without modification of diesel engine parts,
such as a low-pressure pump, high-pressure pump, and injector [7]. It can also be used in diesel engines either as biodiesel oil or after blending with conventional diesel. Previous research has found that carbon monoxide (CO), carbon dioxide (CO₂), particulate matter (PM), hydrocarbons (HC), and sulfur dioxide (SO₂) amounts were decreased in the exhaust gas from biodiesel oil compared with conventional diesel. However, nitrogen oxide (NOx) emission was increased [8].

Currently, biodiesel is gaining popularity as an alternative renewable fuel. It is a clean oxygenated fuel derived through the transesterification of vegetable oils and animal fats. However, biodiesel fuel also has some disadvantages, such as low calorific value, low volatility, high viscosity and poor low temperature properties [9]. The disadvantages of biodiesel in engine operation are decreased combustion pressure (CP), heat release rate (HRR), indicated mean effective pressure (IMEP) and increased brake specific fuel consumption (BSFC) [10–12]. The engine performance and exhaust emission characteristics of a diesel engine are derived differently according to the fuel combustion process in the combustion chamber. In general, the parameters influencing the combustion of fuel in a cylinder include the fuel spray pattern, air swirl, compression ratio, number and size of injector holes, fuel injection pressure, shape and injector location of the combustion chamber, fuel characteristics, engine load and engine speed [11,13–15]. Fuel injection pressure is one of the most important variables affecting the fuel combustion process in the combustion chamber and also affects fuel atomization and formation of the mixture [16–18].

Therefore, the fuel injection pressure is also important in that it specifically affects the engine performance and exhaust emissions.

Many researchers have studied engine performance and emission characteristics when using blends of biodiesel and diesel fuel in different proportions in common rail-compressed diesel engines [19–23].

Jindal et al. [24] investigated the effects of compression ratio and injection pressure in direct injection diesel engine, injected Jatropha methyl ester. Their experimental results confirmed that as the compression ratio and injection pressure were increased, break thermal efficiency (BTE) increased and BSFC decreased. They found that the optimum fuel injection pressure was 25 MPa for a small diesel engine (3.5 kW) used in agriculture and they experimentally confirmed that the compression ratio was 18.

Gumus et al. [25] reported the effect of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled by a biodiesel–diesel fuel blend. Four different fuel injection pressures (18, 20, 22 and 24 MPa) and average effective pressures (12.5, 25, 37.5, 50 kPa) were used with four different engine loads supplied. They experimentally demonstrated a decreased smoke opacity, unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions.

Liu et al. [26] studied the effects of diesel injection pressure on the performance and emissions of a heavy duty (HD) common-rail diesel engine fueled with a diesel/methanol dual fuel. The experimental results show that at a low injection pressure, the IMEP of the diesel methanol dual fuel (DMDF) mode is lower than that of the pure diesel combustion mode. COV_{IMEP} of the DMDF mode first decreases and then increases with increasing injection pressure, and it remained under 2.1% for all the tests.

Yesilyurt et al. [27] investigated the effect of fuel injection pressure on the performance and emission characteristics of a diesel engine using waste cooking oil biodiesel–diesel blends. Compared to diesel fuel, biodiesel fuel showed a decrease in engine torque, brake power, CO, UHC, and smoke opacity, but BSFC, exhaust gas temperature, and NOx and CO₂ emissions increased. On the other hand, the increased injection pressure to 21 MPa increased the engine torque, brake power, and BTE.

Despite these investigations, it is still not completely clear how the fuel injection pressure affects the engine performance and the exhaust emissions of a direct injection diesel engine using a blend with biodiesel oil and standard diesel fuel. Most biodiesel research focuses on the production of biodiesel oil, its fuel characteristics and the application to diesel engines. Therefore, the purpose of this experiment is to investigate the performance and exhaust emission characteristics of the common-rail diesel engine using a blend of biodiesel oil and standard fuel at a specific engine speed. Additionally,
to accurately determine the exhaust emission characteristics, the experiment was carried out with varying fuel injection pressure.

2. Materials and Methods

2.1. Test Fuels and Operating Conditions

2.1.1. Test Fuels

The fuel for the experiment consisted of blends of pure diesel and 0%, 20% and 50% palm oil based on the volume, referred to as PBD0, PBD20 and PBD50, respectively. The selection of fuels used in the experimental engine were characterized by determining their viscosities, densities, flow points, distillation temperatures, flaming points, acidities, ester contents, total glass glycerin and calculated indices of fuel [28–30]. Further, the fuel characteristics of pure diesel and PBD blends were measured using ASTM-D6751 and EN-14214 standard test methods. Fuel characteristics of pure diesel and PBD blend fuels are presented in Table 1.

Table 1. Properties of pure diesel and palm biodiesel (PBD).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Diesel</th>
<th>Palm Biodiesel</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15 °C (kg/m³)</td>
<td>836.8</td>
<td>877</td>
<td>ASTM D941</td>
</tr>
<tr>
<td>Viscosity at 40 °C (mm²/s)</td>
<td>2.719</td>
<td>4.56</td>
<td>ASTM D445</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>43.96</td>
<td>39.72</td>
<td>ASTM D4809</td>
</tr>
<tr>
<td>Calculated cetane index</td>
<td>55.8</td>
<td>57.3</td>
<td>ASTM D4737</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>55</td>
<td>196.0</td>
<td>ASTM D93</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>~21</td>
<td>12.0</td>
<td>ASTM D97</td>
</tr>
<tr>
<td>Oxidation stability (h/110 °C)</td>
<td>25</td>
<td>9.24</td>
<td>EN14112</td>
</tr>
<tr>
<td>Ester content (%)</td>
<td>-</td>
<td>96.5</td>
<td>EN14103</td>
</tr>
<tr>
<td>Oxygen content (wt%)</td>
<td>0</td>
<td>11.26</td>
<td>-</td>
</tr>
<tr>
<td>Sulfur content (wt%)</td>
<td>0.11</td>
<td>0.004</td>
<td>ASTM D5453</td>
</tr>
<tr>
<td>Hydrogen content (wt%)</td>
<td>13.06</td>
<td>12.35</td>
<td>ASTM D5453</td>
</tr>
<tr>
<td>Carbon content (wt%)</td>
<td>85.73</td>
<td>79.03</td>
<td>ASTM D5291</td>
</tr>
</tbody>
</table>

2.1.2. Operating Conditions

In this experiment, PBD oil with 0.004% sulfur content was blended with pure diesel, and the fuel injection pressure was changed from 45 to 65 MPa using these fuel blends. To investigate the characteristics as a function of PBD blending ratio, the engine was sufficiently warmed up to normal operating temperature before the experiment. The pilot and main injection timings were fixed at before top dead center (BTDC) 27 °CA and 3.5 °CA, respectively, to reduce the effects of engine and exhaust emissions due to changes in injection timing. The engine rpm was set to 1700 rpm and the experiment was conducted with engine loads of 50 and 100 Nm. In addition, the coolant temperature of the engine was 80 ± 5 °C and the intake air temperature was maintained at 25 ± 3 °C. The experimental operating conditions are summarized in Table 2.

Table 2. Experiment and operating conditions.

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Unit</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Speed</td>
<td>rpm</td>
<td>1700</td>
</tr>
<tr>
<td>Engine Load</td>
<td>Nm</td>
<td>50, 100</td>
</tr>
<tr>
<td>Cooling Water Temperature</td>
<td>°C</td>
<td>80 ± 5</td>
</tr>
<tr>
<td>Intake Air Temperature</td>
<td>°C</td>
<td>25 ± 3</td>
</tr>
<tr>
<td>Fuel Injection Pressure</td>
<td>MPa</td>
<td>45, 65</td>
</tr>
<tr>
<td>Injection Timing</td>
<td>°CA</td>
<td>Pilot BTDC27/ Main BTDC 3.5</td>
</tr>
</tbody>
</table>
The engine speed was fixed at 1700 rpm to isolate dependence of the fuel injection time on fuel injection pressure. In addition, the engine load was set to 50 Nm or 100 Nm to determine the fuel injection amount as a function of the engine load. The fuel injection timing was set in a range in which the engine operating state was stabilized. Therefore, the pilot injection was fixed at BTDC 27°CA and main injection at BTDC 3.5°CA. Fuel injection pressures were applied at 45 and 65 MPa. The injection timing and duration for different injection pressures are shown in Figure 1. When the injection pressure was increased for an engine load of 50 Nm, the pilot injection duration decreased by 0.06 ms and the main injection duration decreased by 0.17 ms. When the injection pressure was increased and the engine load was 100 Nm, the pilot injection duration was confirmed to decrease by 0.02 ms and the main injection duration decreased by 0.19 ms. Increasing the fuel injection pressure at the same load led to an increase in the fuel injection amount, thereby reducing the fuel injection duration time.

Figure 1. Curves of combustion characteristic of all tested fuels: (a) fuel injection pressure of 45 MPa and engine load of 50 Nm, (b) fuel injection pressure of 65 MPa and engine load of 50 Nm, (c) fuel injection pressure of 45 MPa and engine load of 100 Nm and (d) fuel injection pressure 65 MPa and engine load 100 Nm.

2.2. Test Engine and Experimental Procedure

2.2.1. Test Engine

A four-cylinder in-line turbocharged common rail direct injection diesel engine was used for this experiment. It is equipped with a crankshaft position sensor to detect the engine speed and a combustion pressure sensor to detect the combustion pressure of the combustion chamber. There is also a fuel rail pressure sensor that measures the rail pressure as the fuel pressure changes. To control the operation of the engine in real time, the engine control unit—electronic control unit (ECU) is mounted. Details of the engine are shown in Table 3.
Table 3. Specifications of the test engine.

<table>
<thead>
<tr>
<th>Engine Parameters</th>
<th>Unit</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore × Stroke</td>
<td>mm × mm</td>
<td>83 × 92</td>
</tr>
<tr>
<td>Displacement</td>
<td>cc</td>
<td>1991</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>-</td>
<td>17.7 : 1</td>
</tr>
<tr>
<td>Maximum power/torque</td>
<td>kW/Nm</td>
<td>83.5 (at 4000 rpm)/255 (at 2000 rpm)</td>
</tr>
<tr>
<td>Engine type</td>
<td>-</td>
<td>In-line 4 Cylinder, Turbocharged, EGR</td>
</tr>
<tr>
<td>Number of injector nozzle holes</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Injector type</td>
<td>-</td>
<td>Solenoid</td>
</tr>
<tr>
<td>Injector hole diameter</td>
<td>mm</td>
<td>0.17</td>
</tr>
<tr>
<td>Fuel control</td>
<td>-</td>
<td>ECU</td>
</tr>
<tr>
<td>Manufacture, Model</td>
<td>-</td>
<td>Hyundai Motor, Santafe</td>
</tr>
</tbody>
</table>

2.2.2. Experimental Equipment Set Up

An eddy current dynamometer (DY-230 kW, Hwanwoong Mechatronics, Gyeongsangnam-do, Korea) was installed to control the engine power. In addition, a multi-gas analyzer (HPC501, Nantong Huapeng Electronics, Jiangsu, China) was installed to measure CO, HC, and NOx in the exhaust emissions. A multiple gas analyzer (GreenLine MK2, Eurotron (Korea) Ltd., Seoul, Korea) was installed for accurate and comparative analysis of exhaust emissions. A partial flow collection analyzer (OPA-102, QROTECH Co., Ltd., Gyeonggi-do, Korea) was used to measure particle matter. Combustion pressure for combustion analysis of the combustion chamber was obtained using a piezoelectric pressure sensor (KISTLER Type 6056A, Kistler Korea Co., Ltd., Gyeonggi-do, Korea) at the glow plug position. For analysis of the combustion pressure, data were obtained over an average of 200 cycles. Data acquisition was performed and recorded using a DAQ board (PCI 6040e, National Instrument, Austin, TX, USA). The released particle matter was collected by a copper grid (FCF400-CU, Electron Microscopy Sciences, PA, USA) and transmission electron microscopy (H-7650 TEM, Hitachi Prefecture, Fukuoka, Japan) was used to analyze the shape of the particles. Figure 2 is schematic diagram of the inline experimental equipment.
2.2.3. Data Analysis

The heat release rate is a value calculated based on the combustion chamber pressure using the first law of thermodynamics. The heat release rate represents the progress of normal combustion. The following formula was used to calculate heat release rate \( \left( \frac{dQ}{d\theta} \right) \) [31]:

\[
d\frac{Q}{d\theta} = k \frac{k}{k-1} \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dP}{d\theta}
\]

where \( k \) is the specific heat ratio, \( V \) is the cylinder volume, \( P \) is the combustion pressure, and \( \theta \) is the crank angle. In these experiments, the average value of 200 cycles was calculated to ensure the reliability of the data acquisition. The cylinder volume is a function of the gap volume \( V_c \), cylinder diameter \( D \), the length of the connecting rod \( b \), the radius of the crankshaft \( a \), and the distance between the piston pin and the crankshaft \( L \).

\[
V = V_c + \frac{\pi D^2}{4} (b + a - L)
\]

The ratio of fuel consumption to braking power of an engine is defined as the brake specific fuel consumption. Brake specific fuel consumption data are calculated based on the fuel consumption, engine torque and speed values using the following formula [32]:

\[
BSFC = \frac{m_f}{2\pi NT}
\]

where \( m_f \) is the fuel flow rate, \( N \) is the engine speed, and \( T \) is the brake torque.

To verify the combustion stability of the engine when using the test fuel in the experimental engine, the coefficient of variation (COV) for the indicated mean effective pressure was used. The coefficient of variation is the standard deviation divided by the arithmetic mean, also known as the relative standard deviation. The larger the coefficient of variation, the greater the relative difference. The coefficient of variation of IMEP (COV_{IMEP}) is given by [31]:

\[
COV_{IMEP} = \sqrt{\frac{\sum_{i=1}^{N} (IMEP(i) - X)^2}{\frac{1}{N} \sum_{i=1}^{N} IMEP(i)}}
\]

where IMEP(i) is the indicated mean effective pressure for each cycle. Here, the numerator is the standard deviation of indicated mean effective pressure (IMEP) over 200 cycles (\( N = 200 \)) and the denominator is the average of these values. The brake thermal efficiency is the value of the brake power divided by the thermal energy of the feed fuel [32]:

\[
BTE = \frac{N_e}{B \times H_L}
\]

where \( N_e \) is the brake power output, \( B \) is the fuel consumption per unit time, and \( H_L \) is the low calorific value of the fuel.

3. Results and Discussion

3.1. Combustion Characteristics

3.1.1. Combustion Pressure and Heat Release Rate

Figure 3 shows the combustion pressure and heat release rate when the fuel injection pressure is increased in the biodiesel blended oil in the common rail compressed diesel engine. As seen in the figure, when the engine load was held constant at 50 Nm and the fuel injection pressure was
increased from 45 to 65 MPa, the combustion pressure increased by 9.6, 9.6, and 10.4% for PBD0, PBD20, and PBD50, respectively. Additionally, the heat release rate under the same conditions was confirmed to increase by 12.1, 16.1, 11.2% in PBD0, PBD20, and PBD50, respectively. Keeping the engine load constant at 100 Nm and increasing the fuel injection pressure from 45 MPa to 65 MPa resulted in an increase in combustion pressure by 12.1, 13.5 and 13% for PBD0, PBD20 and PBD50, respectively. In addition, the heat release rate increased by 14.1, 15.4, 9.2% under the same conditions. The reason is the high fuel injection pressure, which improves spraying and mixing. Therefore, fuel evaporation is activated in the boundary layer where compressed air meets injected fuel, resulting in better combustion. Thereby combustion pressure and heat release rate increased with increasing fuel injection pressure [33,34].

![Combustion pressure and heat release rate in the combustion chamber](image)

**Figure 3.** Combustion pressure and heat release rate in the combustion chamber for (a) PBD0 for an engine load of 50 Nm, (b) PBD0 for an engine load of 100 Nm, (c) PBD20 for an engine load of 50 Nm, (d) PBD20 for an engine load of 100 Nm, (e) PBD50 for an engine load of 50 Nm and (f) PBD50 for an engine load of 100 Nm.
Table 4 shows location of the maximum combustion pressure and the maximum heat release rate when the fuel injection pressure is increased. When the engine load was held at 50 Nm and the fuel injection pressure was increased from 45 to 65 MPa, the average time needed to achieve the maximum combustion pressure and maximum heat release rate was approximately 0.098ms faster for all fuels. When the engine load was held constant at 100 Nm and the fuel injection pressure was increased from 45 to 65 MPa, the average time to reach maximum combustion pressure and maximum heat release rate was 0.196 and 0.264 ms faster, respectively for all fuels.

Table 4. Crankshaft angle (ATDC) of the maximum combustion pressure and heat release rate.

<table>
<thead>
<tr>
<th>FIP 1</th>
<th>PBD 0 2</th>
<th>PBD 0 3</th>
<th>PBD 20</th>
<th>PBD 20 4</th>
<th>PBD 50 5</th>
<th>PBD 50 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MPa)</td>
<td>CP 5 (°CA)</td>
<td>HRR 6 (°CA)</td>
<td>CP 5 (°CA)</td>
<td>HRR 6 (°CA)</td>
<td>CP 5 (°CA)</td>
<td>HRR 6 (°CA)</td>
</tr>
<tr>
<td>45</td>
<td>12</td>
<td>15</td>
<td>13</td>
<td>16</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>65</td>
<td>11</td>
<td>13</td>
<td>14</td>
<td>12</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

1FIP: Fuel Injection Pressure. 2 PBD 0: 0% Palm Biodiesel + 100% Diesel. 3 PBD 20: 20% Palm Biodiesel + 80% Diesel. 4 PBD 50: 50% Palm Biodiesel + 50% Diesel. 5 CP: Combustion Pressure. 6 HRR: Heat Release Rate.

3.1.2. Combustion Peak Pressure

To investigate the change in maximum combustion pressure over each cycle, the experiment was carried out over 200 cycles. The fuel injection pressure was then increased from 45 MPa to 65 MPa. The experimental results showed that the average change in maximum combustion pressure for each cycle of the PBD0, PBD20, and PBD50 fuels increased by 10.32% at a 50 Nm engine load.

In addition, it was confirmed that the average change in maximum combustion pressure of each cycle increased by 12.7% in each experimental fuel at an engine load of 100 Nm. Figure 4 shows the maximum combustion pressure as a function of the engine load. Biodiesel’s high viscosity and concentrations can lead to poor spray and volatility, resulting in poor combustion. However, the high oxygen content of biodiesel can improve combustion [11]. Many other researchers have reported that high fuel injection pressure can improve fuel atomization, even for high viscosity biodiesel [35].
3.2. Engine Performance

3.2.1. COVIMEP and IMEP Analysis

An experiment was conducted to find out the change of the indicated mean effective pressure in the experimental engine. Figure 5a,b shows the change in IMEP, when fuel injection pressure was increased from 45 to 65 MPa, IMEP slightly increased by 0.95%, 8.5% and 3.8% for PBD0, PBD20 and PBD50, respectively. In addition, under the same conditions for 100 Nm of engine load, IMEP slightly increased by 2.2%, 6.2% and 2.8% when using PBD0, PBD20 and PBD50, respectively.

In this experiment, we also determined the COVIMEP values. As seen in Figure 5c,d, the COVIMEP values for the 50 and 100 Nm engine loads are less than 1.6% and 0.9%, respectively, when the fuel injection pressure is changed. This shows that the combustion state of the engine works well within 200 cycles. The increase in fuel injection pressure is evidence that the difference in combustion pressure between each cylinder in the four-cylinder cylinder is not large and is relatively uniform. In addition, the COVIMEP value with respect to the biodiesel oil blend rate is lower than that of pure diesel. This is likely because palm oil itself has higher oxygen content than pure diesel oil [21].

3.2.2. BSFC Analysis

As shown in Figure 6, the BSFC with respect to the engine load exhibited an average value that was 16.3% lower for the engine load of 100 Nm than for the engine load of 50 Nm. For an engine load of 50 Nm, BSFC was reduced by an average of 2.43% when the fuel injection pressure was increased from 45 MPa to 65 MPa. In addition, the BSFC for the 100 Nm engine load showed an average reduction of

![Figure 5. IMEP for engine loads of (a) 50 Nm and (b) 100 Nm. COVIMEP for engine loads of (c) 50 Nm and (d) 100 Nm.](image-url)
0.8% when the fuel injection pressure was increased from 45 MPa to 65 MPa. However, comparing the BSFC of pure diesel and biodiesel blends shows that BSFC values are increased in the biodiesel blends. The average value of BSFC increased with increasing biodiesel blended at 50 Nm of engine load. BSFC increased 4.07% and 1.91% at 45 and 65 MPa fuel injection pressures, respectively. In addition, the average value of BSFC increased with increasing biodiesel blended at 100 Nm engine load. BSFC increased 5.83% and 3.7% at 45 and 65 MPa fuel injection pressure, respectively. This is because the density and kinematic viscosity of biodiesel oil (877 kg/m³, 4.56 mm²/s) is higher than that of pure diesel (836.8 kg/m³, 2.719 mm²/s) and the lower calorific value is lower than that of pure diesel [25,36,37].

Figure 6. BSFC for engine loads of (a) 50 Nm (b) 100 Nm.

3.3. Emission Characteristics

3.3.1. HC and PM

Figure 7a,b shows that the HC emissions decreased by 29.6%, 19% and 12.5% for PBD0, PBD20, and PBD50, respectively, when the fuel injection pressure was increased from 45 to 65 MPa for a 50 Nm engine load. In addition, when the fuel injection pressure was increased from 45 MPa to 65 MPa for a 100 Nm engine load, HC emissions decreased by 24%, 15% and 18.2% using PBD0, PBD20 and PBD50 fuels, respectively. As the proportion of biodiesel oil and fuel injection pressure increased, HC emissions decreased because the high amount of oxygen in the biodiesel itself reduces the amount of unburned HC in the exhaust [25,38].

In general, the biodiesel with high oxygen content can effectively deliver oxygen to the pyrolysis zone of combustion spray to reduce smoke emission. In addition, the oxygen in biodiesel ensures post-flame oxidation and increases flame speed during air-fuel interaction resulting in complete hydrocarbon oxidation [39,40]. Figure 7c,d shows the PM emissions when the fuel pressure was increased from 45 to 65 MPa using PBD0, PBD20, and PBD50 for engine loads of 50 Nm and 100 Nm. For an engine load of 50 Nm, the PM emissions decreased by 59.5%, 51.6%, and 52.1% using PBD0, PBD20, and PBD50, respectively, under these conditions. Additionally, when the fuel pressure was increased from 45 MPa to 65 MPa for an engine load of 100 Nm, the PM emission decreased by 41.7%, 43.5%, 52.7% using PBD0, PBD20, and PBD50, respectively. Overall, PM emissions of all tested fuels decreased with the increase of fuel injection pressure from 45 to 65 MPa. This is because biodiesel itself contains high oxygen content, which can improve the combustion environment of fuel even under partial oxygen deficiency conditions [25,41].
3.3.2. Particulate Matter Characteristics

As shown in Figure 8, transmission electron microscopy (TEM) images were taken to investigate the dependence of PM emission characteristics on the engine load and fuel injection pressure. Figure 9 shows a graph of the mean particle diameter, measured by analyzing the diameter of the PM as well as the shape of the PM using TEM micrographs. When the engine load was 50 Nm and the fuel injection pressure was increased from 45 MPa to 65 MPa, the diameter of PM decreased by 4.7%, 2.5% and 0.4% on average in PBD0, PBD20 and PBD50, respectively. In addition, when the engine load was 100 Nm and the fuel injection pressure was increased from 45 MPa to 65 MPa, the diameter of PM decreased by 11.7%, 6%, and 2% on average in PBD0, PBD20, and PBD50, respectively. As a result, it was confirmed that the exhaust particle size of PM was reduced by increasing the fuel injection pressure [11,42].

Figure 7. HC emissions in the exhaust gas for engine loads of (a) 50 Nm and (b) 100 Nm. PM in the exhaust gas for engine loads of (c) 50 Nm and (d) 100 Nm.
Figure 8. TEM images of the PM emissions for different engine loads and fuel injection pressures changes.

Figure 9. Average particle size of PM emissions for different engine loads of (a) 50 Nm (b) 100 Nm.

3.3.3. CO and NOx

CO emission from PBD0, PBD20, and PBD50 fuels used at engine loads of 50 and 100 Nm are shown in Figure 10a,b for when the fuel injection pressure is increased from 45 MPa to 65 MPa. For an engine load of 50 Nm, this fuel injection pressure increase resulted in CO emission decreases of 6.1%, 9.7% and 7.4% when using PBD0, PBD20 and PBD50, respectively. In addition, CO emissions from PBD0, PBD20 and PBD50 decreased by 6.3%, 9.5% and 8.9% with this fuel injection pressure increase for an engine load of 100 Nm. From the above results, as the biodiesel blended rate and fuel injection pressure were increased, the CO emissions were decreased compared to pure diesel. This is because biodiesel itself contains about 11% oxygen, which can promote fuel towards complete combustion. Increasing the fuel injection pressure resulted in a good mixture of air and fuel, creating...
good combustion environment, resulting in reduced CO emissions. Other researchers also reported similar results [25,43].

In addition, NOx emissions from PBD0, PBD20, and PBD50 increased by 35.8%, 35.9% and 34.9%, respectively, for a 100 Nm engine load. On the other hand, the NOx emissions of PBD20 and PBD50 were respectively increased by about 1.7% and 1.5% according to 45 and 65 MPa. The NOx emissions increased as the biodiesel blended rate and fuel injection pressures were respectively controlled at 45 and 65 MPa at an engine load of 50 Nm; for an engine load of (a) 50 Nm and (b) 100 Nm and NOx from engine loads of (c) 50 Nm and (d) 100 Nm.

Figure 10. Exhaust gas emissions of CO from engine loads of (a) 50 Nm and (b) 100 Nm and NOx from engine loads of (c) 50 Nm and (d) 100 Nm.

NOx emission also changed for engine loads, fuel injection pressures, and fuel blends. The formation of NOx emissions is mainly related to the high temperature conditions in the combustion chamber. In general, the oxygen content in biodiesel increases the highest temperature in combustion chamber compared with that in diesel fuel with no oxygen content. The NOx emissions emitted from diesel engine is predominantly composed of NO, and with lesser amounts of NO2 [44]. When the temperature in the combustion chamber exceeds 1700 K, a series of chemical reactions occur between N2 and O2 through Zeldovich mechanism to form a lot of NOx emissions [45]. The basic equation for the formation of NOx is listed in chemical reactions 6–8. High cetane number of biodiesel can shorten ignition delay, and high oxygen content can ensure better combustion resulting in higher cylinder temperature [46]. Therefore, the higher the oxygen content in fuel, the more the formation of NOx emissions.

\[
N_2 + O \leftrightarrow NO + N \tag{6}
\]

\[
N + O_2 \leftrightarrow NO + O \tag{7}
\]

\[
N + OH \leftrightarrow NO + H \tag{8}
\]

As shown in Figure 10c,d, NOx emissions increased by 30.8%, 31.3% and 35.6% for an engine load of 50 Nm using PBD0, PBD20, and PBD50, respectively, as the fuel injection pressure increased. In addition, NOx emissions from PBD0, PBD20, and PBD50 increased by 35.8%, 35.9% and 34.9%, respectively, for a 100 Nm engine load. On the other hand, the NOx emissions of PBD20 and PBD50 were respectively increased by about 0.7% and 2.8% on average compared to PBD0, when the fuel injection pressures were respectively controlled at 45 and 65 MPa at an engine load of 50 Nm; for 100 Nm engine load, the NOx emissions were respectively increased by about 1.7% and 1.5% according to 45 and 65 MPa. The NOx emissions increased as the biodiesel blended rate and fuel injection
pressure increased, due to the presence of the high chemically bound oxygen content in biodiesel compared to pure diesel, which resulted in increasing of combustion temperature and pressure in the combustion chamber. Other researchers reported that the oxygen content in biodiesel fuel plays an important role for formation of NOx emissions [25,47].

4. Conclusions

This study was conducted to investigate combustion and exhaust emission characteristics at 50 and 100 Nm engine loads using PBD0, PBD20, and PBD50 fuels in a common rail diesel engine as the injection pressure is increased from 45 to 65 MPa.

The combustion pressure and heat release rate increased with increasing fuel injection pressure for engine loads of 50 and 100 Nm. IMEP also increased when the fuel injection pressure increased for 50 and 100 Nm engine loads. COVIMEP values are less than 1.6% and 0.9% for the engine loads of 50 and 100 Nm, respectively, with increasing fuel injection pressures. When the fuel injection pressure was increased for an engine load of 50 Nm, the BSFC was reduced on average by 2.43%. Additionally, when the fuel injection pressure was increased for 100 Nm of engine load, the BSFC decreased by 0.8% on average. HC emissions were reduced for all fuels tested with increasing fuel pressure for 50 and 100 Nm engine loads. As the biodiesel oil content increased, the emission of HC decreased. PM decreased when the fuel pressure was increased from 45 to 65 MPa for both 50 and 100 Nm engine loads. CO emissions decreased when the fuel injection pressure was increased for an engine load of 50 Nm when using PBD, PBD20 and PBD50. CO emissions were also reduced with increasing fuel injection pressure for a 100 Nm engine load in PBD0, PBD20 and PBD50. As fuel injection pressure and biodiesel content were increased, CO emissions were decreased compared to pure diesel. When the fuel injection pressure was increased from 45 MPa to 65 MPa, NOx emissions were increased for 50 and 100 Nm engine loads. For a given fuel injection pressure, the amount of NOx emissions increased slightly as the biodiesel content in the fuel blend increased.

Author Contributions: S.K.Y. performed the experiments, analyzed all experimental data, and wrote this paper. J.C.G. performed the experiments and contributed to engine performance analysis. N.J.C. designed this experiment and contributed to the data analysis supervised the experiment and the paper. All authors participated in the evaluation of the data, reading and approving the final manuscript.

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