Full Length Article

Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels

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\begin{abstract}
Biodiesel can be used as alternative to replace fossil diesel. However, usage of biodiesel in an unmodified diesel engine can cause higher in nitrogen oxides (NO\textsubscript{x}) emission. In order to reduce the harmful emission, certain injection strategies can be carried out. In this paper, the effects of biodiesel blends, fuel injection timing and split injection schemes on the engine performance, emissions and combustion characteristics of a medium-duty diesel engine are investigated. Parametric studies relating with start of injection timing variation and multiple injection schemes using B20 and B50 biodiesel blends were performed and benchmarked with petroleum diesel fuel as baseline. A remarkably lower NO\textsubscript{x} level below 100 ppm can be obtained by retard start of injection (SOI) timing for both of the B20 and B50 fuel operations and with triple injection scheme. It was found that with the use of B50, simultaneous NO\textsubscript{x} and smoke suppression from the levels of petroleum diesel fuel is attainable in parallel with the implementation of late SOI timing and triple injection scheme in a diesel engine. In conclusion, multiple split injections is a practical strategies to simultaneously decrease NO\textsubscript{x} and smoke emissions when the SOI timing is fine-tuned and is an ideal alternative to operate with biodiesel fuel.
\end{abstract}

1. Introduction

The widespread use of diesel engine has caused air pollution problems. This is due to their higher exhaust discharges of nitrogen oxides (NO\textsubscript{x}), particulate matter (PM) and smoke in comparison with that of a gasoline engine [1]. The air pollutants jeopardize human health in different ways, necessitating the needs to curb this problem [2–4]. To minimize this impact, research effort are being focused on injection strategies such as variable injection timing, split injection, variable injection pressure, variable nozzle configuration, and others [5,6]. Injection timing optimization can be performed in order to produce a suitable ignition delay as well as to reduce the amount of exhaust emission in diesel engine. For instance, advancing the injection timing reduces the amount of carbon monoxide (CO), hydrocarbon (HC) and smoke while increases the amount of NO\textsubscript{x} emitted [5]. More time is available for oxidation when injection is advanced, thus reducing the amount of CO, HC and smoke, but with higher amount of NO\textsubscript{x} emitted. In order to reduce amount of NO\textsubscript{x} emitted, the injection can be carried out later to lessen the air temperature even though at the expense of increasing the amount of CO, HC and smoke emitted due to incomplete combustion.

Another strategy can be implemented to diesel engines to attain lower emission limit is by split injection. It can be carried out to reduce engine noise and amount of NO\textsubscript{x} emitted. Furthermore, accurately performed split injection schemes can be favorable in reducing combustion noise, waste emissions and diesel consumption and therefore, they are effective tools [7]. Besides, particulate emissions can be reduced substantially without a great increase in NO\textsubscript{x} emissions [8,9]. This is because high heat release rate (HRR) can be prevented at the beginning of combustion, hence decrease the flame temperature and permit better fuel and air mixing to enhance in-cylinder charge homogeneity. Besides, energy demands of the world are increasing nowadays. Depletion of fossil diesel fuel can be slowed by adopting renewable source of energy such as biodiesel. Biodiesel can be made from vegetable oil, animal fat or waste materials such as spent coffee grounds [10]. Also, it is nontoxic, renewable and biodegradable...
compared to conventional diesel [11]. Generally, CO, smoke and particulate matter concentration emitted when biodiesel is used are lower compared to conventional diesel [12,13]. However, NOx emission of biodiesel can be higher or lower for different types of biodiesel and operating condition [12,14]. Biodiesel has cetane number which is higher than ordinary petroleum diesel, which implies that it has a better ignition properties and higher combustion efficiency [12,15,16]. Biodiesel evaporates, atomizes and breaks up slower because it has a higher kinematic viscosity and surface tension. Hence, it is important to apply a suitable injection strategies to overcome this problem.

The increasing of world population has rapidly increasing the energy demand from non-renewable resources [17]. Biodiesel fuels have gained increasing attention worldwide as blending components or direct substitution for diesel engines [18]. However, the utilization of biodiesel in diesel engines has usually produced higher NOx and brake specific fuel consumption [19–21]. Using alternative fuels and optimization of fuel injection parameters in diesel engine can be reliable methods to solving this problem. According to Shivakumar et al. [22] in the research of effects of biodiesel and injection timing on single-cylinder diesel engine performance, NOx emission of waste cooking oil blended fuel is relatively higher than that of baseline diesel. It is found that the NOx emission will be lower at retarded injection timing for baseline diesel and biodiesel. The smoke emission of biodiesel is less than baseline diesel and the advanced injection timing will reduce the smoke reduction of both kinds of diesel. Qi et al. [23] showed that NOx emission always decreases with the retarding injection timing when using biodiesel produced from soybean as energy source in six-cylinder diesel engine. Sayin et al. [24] and Ganapathy et al. [25] also obtained the same results as Shivakumar et al. [22] when Jatropha biodiesel are used correspondingly in their researches by using single-cylinder diesel engine. Recently, modern engines are trending toward multiple fuel injection events as a means to decrease emissions and improve engine performance [26,27]. In the investigation of effects of split injection on the emissions of biodiesel, Fang et al. [28] found that NOx emission of biodiesel can be 34% lower than baseline diesel under certain injection scheme at specific condition in single-cylinder diesel engine. The injection strategies used in their study included double injection of a small first injection with an early pre-TDC (top dead center) timing and followed by a main injection at or after TDC. Joonho Jeon et al. [29] discovered that retardation of pilot injection timing will cause increasing amount of NOx emission when soybean biodiesel is used in single-cylinder diesel engine. Kuen Yehliu et al. [30] showed that under single injection scheme in four-cylinder diesel engine, the amount of emission of NOx is higher for biodiesel compared to baseline diesel. However, when split (pilot and main with non-equal fuel quantity) injection scheme is carried out, the NOx emission is the lowest for biodiesel. The drawback is that there will be an increase in particulate matter emitted when biodiesel and baseline diesel are used when split injection scheme is carried out. Su Han Park et al. [31] studied about the relationship of injection timing and split injection (with up to two injections per combustion cycle) with the performance of biodiesel by using a single-cylinder diesel engine. They found that NOx emission increases with advanced injection timing. Multiple injection scheme cause less soot to be emitted compared to single injection scheme except at highly advanced injection timing. The retardation of pilot injection timing reduces the amount of soot emitted. Besides, multiple injection strategy has been proposed as an effective way to reduce unburned emissions and noise [32,33].

From the previous works, it is evident that most of the studies have been focused on experimental research of biodiesels in which few experiments were conducted with injection timing variation and split injection, specifically dealing with two or more fuel injections of equal quantities per combustion cycle. Besides, although the above mentioned literature reported the studies of split injection engine combustion, but most of them have been performed on single-cylinder research engine, which is not practical representative of the production engine adopted in commercial vehicles. Thus a research gap remains in these fields which are addressed in this research study. The outcome due to changes in biodiesel blends, injection timing and split (with up to three injections of equal fuel quantity) injection schemes on a four-cylinder medium-duty diesel engine will be investigated in the present study. From the results, the effect of each of the injection strategy will be determined to enhance the research in developing biodiesel to overcome the air pollution and fossil fuels depletion issues.

2. Experimental apparatus and procedure

2.1. Apparatus setup

The experimental study was implemented using three types of fuel sample. The samples consist of diesel, B20 (in a volume fraction of 20% biodiesel blends and 80% diesel) and B50 (in a volume fraction of 50% biodiesel blends and 50% diesel) of coconut oil biodiesel (COB) blends. A four-cylinder diesel engine with Delphi common-rail fuel injection system and turbocharger set up was utilized in the research. Variation of speeds and loads was controlled using eddy current engine dynamometer with rating of 150 kW. Measurement of engine fuel consumption was done by employing Kobold fuel flow meter. Temperatures of surrounding air, engine lubricant oil, exhaust gas emitted and engine coolant were obtained by using K-type thermocouples. Table 1 shows the specifications and information of test engine.

Commercially available microcontroller was used as the engine control module (ECM). The microcontroller employed three interrupt service routines in order to receive the signals from incremental encoder and engine camshaft. Besides, a C programming language was used in programming coding. The codes were uploaded to microcontroller through serial communication with personal computer. A graphic user interface (GUI) program was created using LabVIEW to manipulate and examine the engine parameters including start of injection (SOI) timing, engine speed, opening pulse-width (PW) and number of injections (single, double and triple injection) and closed-loop engine speed control mode selection. Quantity of diesel injected was regulated by a dedicated engine speed controller to maintain engine rpm to within ±10 rpm (revolution per minute) from the set point. This engine speed controller comprised a fine-tuned proportional-integral (PI) control loop. By deploying this approach, the speed controller could reject a huge amount of disturbance and minor steady-state error spanning the whole engine operating range. In addition, programmable peak and hold pulse-width-modulation (PWM) was incorporated in engine controller to control the solenoid injectors for common-rail direct injection efficiently. Engine parameters could be fully controlled by this specifically designed control unit.

To execute the combustion process analysis, the gas pressure in cylinder was obtained with a Kistler 6058A piezoelectric sensor and high speed data acquisition system was used to record its signal. Glow plug adapter was utilized so that pressure sensor could be fixed in the first cylinder’s head. DAQ-Charge-B charge amplifier was employed to enlarge the signal from pressure sensor. Incremental encoder with the

### Table 1
Specifications and information of the test engine.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Engine</td>
<td>Diesel, 4-stroke, turbocharged direct injection engine</td>
</tr>
<tr>
<td>Fuel injection supply system</td>
<td>Diesel common-rail with rail pressure 140 MPa max.</td>
</tr>
<tr>
<td>Cylinder</td>
<td>4</td>
</tr>
<tr>
<td>Valve per each cylinder</td>
<td>2</td>
</tr>
<tr>
<td>Bore x stroke</td>
<td>76.0 mm × 80.5 mm</td>
</tr>
<tr>
<td>Connecting rod length</td>
<td>135 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>1461 cm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>18.25–1</td>
</tr>
<tr>
<td>Maximum power &amp; torque</td>
<td>48 kW at 4000 rpm &amp; 160 Nm at 2000 rpm</td>
</tr>
</tbody>
</table>
resolution of 0.125°CA (crank angle) was used to measure the crankshaft rotation angle. Cylinder pressure data for 100 consecutive engine revolutions were collected and averaged for each test. Fig. 1 shows the schematic diagram of the experiment setup. Regarding pollutant emission evaluation, concentrations of NOx was measured by using AVL DICOM 4000 gas analyser while AVL DiSmoke 4000 was set up to obtain smoke opacity.

2.2. Experimental procedure

Usually, engines used for medium-duty diesel powered urban vehicles are operated under partial load condition. For this reason, part load operation is considered in choosing the experimental cases. In the present engine testing, the engine speed is held constant at 2000 rpm and with 60 Nm of torque. The influences of biodiesel blended fuels on engine out-responses, such as combustion, tail-pipe emissions and performance characteristics under different split injection approach (single, double and triple) and injection timing (−12°ATDC to 2°ATDC) conditions were studied. Split injection approach can be implemented by dividing the single injection event into two or three consecutive equal injection events for each engine combustion cycle with certain dwell timing between consecutive injections. The advantages of this injection strategy is that it reduces combustion flame temperature and enables ample fuel and air mixing so that charge homogeneity can be improved. Fig. 2 delineates the timing schemes for single, double and triple injection strategies studied in the present work. Obviously, the investigated approaches vary in the splitting schematization of main injection. Firstly, single injection was carried out in the fuel injection event. During second approach, the fuel injection process was performed by two similar injection pulses, while in the third fuel injection event three equal amount injection pulses were introduced. It has to be emphasized that the strategy of splitting the single injection pulse into two and three identical pulses was that the sum of entire engine power was fixed for every profile and SOI timing. In each test scheme, a commercial diesel fuel was used to operate the engine at room temperature, it functioned adequately over the entire test and there was no starting difficulty. The tests were conducted when the steady-state conditions were achieved. Exhaust gas was warmed sufficiently and water coolant was maintained at suitable temperature. The important properties of the petroleum diesel, B20 and B50 are listed in Table 2. Every test case was repeated for two times to obtain average value in order to improve the accuracy in the study. Repeatability was as high as 95% for every case tested.

2.3. Biodiesel property test

After transesterification process was completed, the methyl ester produced was thoroughly inspected its fuel properties and comparison with biodiesel standards was made. Table 2 shows the detail of the crucial physicochemical properties possessed by the converted neat COB compared with ASTM (American Society for Testing and Materials) standard. The essential properties of fossil diesel fuel are also shown in that table. ASTM D6751 has been used as biodiesel standard where measured physiochemical properties of biodiesel produced were benchmarked against it. It shows that the converted COB has all the physicochemical properties complied with the ASTM and biodiesel standard. Notably, the kinematic viscosity of the transesterified coconut oil was improved considerably. However, it was marginally greater than that of conventional diesel. Besides, COB had a higher flash point than conventional diesel and therefore suitable to be utilized as transportation fuel. The drawback is that COB possess lower calorific value compared to petroleum diesel fuel. Another factor which influences engine combustion characteristics and performance is the distillation temperature of fuel. Commonly, distillation temperature can act as a parameter for checking fuel quality while information about volatility, flash point and fatty acid composition can be obtained by examining the distribution range. In this research, the entire ranges of distillation temperatures of the fuel sample Tx, in which “x” means distillation temperatures corresponding to x vol% of the distilled and condensed
number with biodiesel blend ratio is illustrated in Table 3. It is observed that the cetane number increases linearly with an increase in the biodiesel blend ratio. The linear relationship between the cetane number and the biodiesel blending ratio was obtained by Acharya et al. [34], and has been considered in this study. The cetane number (Y) of the biodiesel blends was calculated from the% volume fraction of biodiesel blend (X) using the following formula:

\[ Y = 0.043X + 52.4 \]  

(1)

2.4. Statistical and equipment uncertainty analysis

Generally, all experimental measurement are subject to some uncertainties or errors. The uncertainty in an experimental result can arise from sensor selection, condition, calibration, observation and test procedure. The summary of the equipment used in this study including the measurement range and accuracy of the instruments is given in Table 4. Uncertainty analysis is essential to verify the accuracy of the experiments. Hence, the percentage uncertainties of various parameters such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were determined based on the percentage uncertainties of the instruments used in the experiments. The uncertainty analysis was performed using the method described by [35]. The overall experimental uncertainty was determined using the following equation:

Overall experimental uncertainty

\[ \text{Overall uncertainty} = \sqrt{(\text{uncertainty of Fuel Flow Rate})^2 + (\text{uncertainty of Crank angle encoder})^2 + (\text{uncertainty of Pressure sensor})^2 + (\text{uncertainty of Smoke})^2} \]

\[ = \sqrt{(0.043)^2 + (1.9)^2 + (1.3)^2 + (1)^2 + (0.5)^2 + (0.03)^2} = \pm 2.9\% \]
3. Results and discussion

3.1. Performance characteristics

Effects of biodiesel blends, injection timing variation and split injection scheme on BTE and BSFC are discussed in the following section. Fig. 3 delineates the changes in BTE with various SOI timings and split injection schemes of the engine fuelled with B20, B50 and baseline diesel. It was found that the BTE for baseline diesel is constantly higher than that of B20 and B50 at any SOI timing. Literally, peak BTE of baseline diesel, B20 and B50 are observed to be 33.5%, 32.6% and 32.1% respectively at SOI timing equals −12°ATDC and with single injection scheme. Besides, the outcomes also show that difference in SOI timing profoundly affects BTE. Advanced SOI timings cause in- crement in BTE for all fuel type tested. The improvement is attributable to the longer ignition delay (physical delay) which in turn brings about a better mixing. This results in more efficient combustion and a greater BTE. Another explanation can be made where at advanced injection timing, the engine attains peak combustion pressure near to TDC. Hence, greater effective pressure can be produced to generate useful work [36]. Nonetheless, for the corresponding SOI timing, there is a perpetual decline of BTE by an average of 5.2% and 13.1% for the case of double and triple injection, respectively, in comparison to the BTE of single injection operation using baseline diesel. It may be due to the combustion process occurs over a longer period for double and triple split injection. Thus, the heat losses through the cylinder wall is increases due to longer combustion duration, and consequently less useful mechanical work is generated. Another explanation is that the power output is reduced because a greater quantity of fuel is combusted when the cylinder expansion occurs. Subsequently, the cylinder pressure increases only when volume of cylinder is expanding quickly. Therefore, a smaller effective pressure will be produced. Another observation is that when single injection scheme is implemented at SOI of −12°ATDC, it is found that BTE decreases with increasing of biodiesel blend. This trend is discovered for other SOI and split injection scheme, which is in accordance with other researches [30,37]. The lower BTE can be due to the fact that diesel engine used in the present study is not purposely designed for the use of biodiesel. Besides, with the addition of biodiesel fuel in the blend, the oxygen content is richer than that of conventional diesel. This causes biodiesel blended fuels to have a lower calorific value in comparison to baseline diesel properties as shown in Table 2. The lower heating value of B20 and B50 than that of petroleum diesel, which was about 1.4% and 5.4%, respectively less than heating value of petroleum diesel fuel. Moreover, it is discovered that the changes in injection timing has caused impact on the magnitude of the BSFC. Reduction in BSFC can be achieved by advancing the SOI timing from 2°ATDC when different types of diesel are used. When SOI was implemented earlier, there was continuous improvement in combustion effectiveness and quality. This explains the decrement in BSFC. As BSFC decreases under fixed value of brake power output, less amount of fuel is being injected to enable a more efficient combustion process to occur. This occurs particularly when earlier SOI timing is set. In addition, it can be noticed that for the respective SOI timing, the BSFC is increased with the increasing in number of split injections for all fuels. These results are consistent with other researchers [38,39]. By diving the main fuel injection into two and three parts reduced the peak

### Table 4

List of measurement range, accuracy and percentage uncertainties.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Measurement range</th>
<th>Accuracy</th>
<th>Measurement techniques</th>
<th>% Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>± 600 Nm</td>
<td>± 0.1 Nm</td>
<td>Strain gauge type load cell</td>
<td>± 0.25</td>
</tr>
<tr>
<td>Speed</td>
<td>0–10,000 rpm</td>
<td>± 1 rpm</td>
<td>Magnetic pick up type</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Time</td>
<td>−</td>
<td>± 0.1 s</td>
<td>−</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Fuel flow measurement</td>
<td>0.5–36 L/hr</td>
<td>± 0.04 L/hr</td>
<td>Positive displacement gear wheel flow meter</td>
<td>± 0.5</td>
</tr>
<tr>
<td>NOx</td>
<td>0–5000 ppm</td>
<td>± 1 ppm</td>
<td>Electrochemical</td>
<td>± 1.3</td>
</tr>
<tr>
<td>Smoke</td>
<td>0–100%</td>
<td>± 0.1%</td>
<td>Photodiode detector</td>
<td>± 1</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>0–25,000 kPa</td>
<td>± 10 kPa</td>
<td>Piezoelectric crystal type</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Crank angle encoder</td>
<td>0–12,000 rpm</td>
<td>± 0.125°</td>
<td>Incremental optical encoder</td>
<td>± 0.03</td>
</tr>
<tr>
<td>Computed</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

Fig. 3. BTE and BSFC for various fuels, start of injection timings and split injection schemes.
Combustion pressure, thus lower the amount of fuel injected when TDC is reached. This causes reduction in work done. Another possible explanation is that it may be due to the longer combustion duration, thus increased the heat loss when higher number of split injections is being used. As a result, BSFC has to be increased to supply more energy.

3.2. Emissions characteristics

Effects of biodiesel blends, injection timing and split injection scheme on NOx and smoke emissions amount are discussed in this section. The trend of NOx emissions when various test fuels are used at different SOI timings as well as split injection schemes is displayed in Fig. 4. It is found that advanced SOI timing causes an increase in NOx emission amount for all fuel types and multiple injection scheme. Increasing trend is observed in NOx emissions when SOI timing is advanced. This condition suggests that the ignition and combustion of mixture occur earlier and result in early formation of peak pressure around TDC. This causes the combustion to happen at a higher temperature and promotes the thermal or Zeldovich NOx formation mechanism. The results also imply that both B20 and B50 biodiesel blends tend to diminish NOx emissions over all SOI timings and split injection strategies. This is due to the rather greater cetane number and smaller calorific value of the B20 and B50 in comparison with baseline diesel as depicted in Table 3. The factors subsequently reduce the heat release rate during the premix combustion phase and lower the peak combustion temperature. The discovery can be explained by comparing the in-cylinder mean gas temperature results depicted in Fig. 7. Besides, a considerably lower NOx emission level under 100 ppm can be attained by applying late SOI timing for B20 and B50 fuel operations and with triple injection scheme. With injection performed lately, the retardation of combustion phasing will happen progressively in the expansion stroke and moves away from TDC. This effect causes a decrease in combustion gas temperature and reducing NOx formation. Meanwhile, dividing the main injection into two and three parts lowered the NOx emissions. This can be attributed to the improvements made in the injection process of modulating the injection rate for multiple injection strategy, thus splitting the heat release process into separate portions and reduced in peak rate of heat release. This shows that split injection is effective in reducing NOx emissions. The smoke formed due to the unfinished combustion of the hydrocarbon in the fuel and partial oxidation of the carbon content in the fuel. The amount of smoke emissions of each test fuel at different SOI timings and injection schemes is delineated in Fig. 4. Overall, it is discovered that drop in level of smoke emission occurs when B20 and B50 are employed at every SOI timing. Less smoke was emitted than when diesel fuel is utilized at each SOI timing, mainly due to richer fuel-borne oxygen, less carbon content, and the absence or lesser quantity of aromatics hydrocarbon in biodiesel blends. The results also indicate that with advanced SOI timings, the smoke emissions were reduced when double injection strategy is carried out, and somewhat remained unchanged during operation of single injection strategy. This is because when SOI timing is advanced, gas temperature developed will be higher, in which fuel and oxygen reaction will be improved. As a result, both injection schemes will yield lower emission level of smoke. The second possible reason is the presence of enough time for the fuel to vaporize and form mixture with air, thus allowing effective mixing and complete combustion. However, the triple injection scheme operation shows slightly higher smoke emission with earlier SOI timings. It may be due to the decrease in the in-cylinder combustion temperature (as shown in Fig. 7) that prevent high burn rates, which leads to incomplete combustion with increased smoke emissions. This implies that multiple injections are able to jeopardize smoke emissions level when the optimization of injection timing is not implemented well. By operating the engine with B50 fuel, smoke emission can be diminished without affecting the reduction effect in NOx emissions amount. The results show that a similar smoke emission level (i.e. below 6% for diesel operation with single injection scheme) can be obtained when the B50 is used along with the strategies of retarded SOI timing and triple injection scheme. Therefore, simultaneous decrease in NOx and smoke emission level from the baseline levels of pure diesel is achievable with the usage of B50 biodiesel blended fuel in conjunction with the application of retarded SOI timing and triple injection scheme in a diesel engine.

3.3. Combustion characteristics

To investigate the influence of injection scheme and types of fuel on combustion characteristics, 100 consecutive cycles of cylinder combustion pressure were logged and processed. The average values were calculated and compared. Fig. 5 depicts the graphs of injector current profile, combustion pressure and HR of the engine, utilizing baseline diesel at SOI of 6°ATDC (nominal timing) and with various injection strategies. From the injector current profile, it can be seen that the fuel injection event was formed by two and three identical injection pulses for double and triple injection schemes, respectively. Besides, the engine operated with multiple injection schemes had significant impact on the combustion process. The crank angle position of peak pressure was advanced towards the compression stroke with greater number of injection schemes. Also, the location of start of combustion (SOC) timing for double and triple injection scheme occurred 0.5°CA and 1°CA respectively, more advanced than that of single injection scheme. Additionally, in double injection test case, peak pressure undergoes a minor decline in the range of 1.7 bar. However, triple injection strategy

![Fig. 4. NOx and smoke emission for various fuels, SOI timings and injection strategies.](image-url)
has resulted in a slight increase in the range of 1 bar was discovered for peak pressure. Two and three notable HRR peaks can be noticed for double and triple injection strategies, respectively. Besides, it can be seen that the occurring position for the first peak of HRR curve, when double and triple injection strategies are conducted, is shifted earlier by 0.5°CA and 1°CA respectively, in comparison with single injection strategy. The main cause for the first HRR peak timing to occur early is the advanced occurrence in SOC timing and subsequently leads to the earlier HRR rise. Besides, the two diffusion burns resulting from the subsequent fuel pulses occur at about the same time after start of injection for both timings (ignition delay_2 is approximately same with ignition delay_3) but lower intensities are evidently seen. The second and third fuel pulse ignite almost immediately soon after the SOI_2 and SOI_3 since they are directly injected into the main combustion zones.

Fig. 6 indicates the plot of combustion pressure and HRR variations as a function of crank angle at various SOI timings, single injection strategy and with all types of fuel tested. Overall, the pressure peak of combustion constantly rises and advances towards the location of TDC with earlier SOI timing for all fuels. Greater effective work can be generated via the larger pressure and this helps in enhancing BTE and reducing BSFC. Besides, the HRR plots also exhibit a resembling pattern as that of combustion pressure in which first peak of HRR associated with the premixed combustion phase was advanced towards compression stroke with earlier SOI timing when different fuels are utilized. With SOI timing advancement toward the TDC point in cylinder expansion stroke, the peak HRR correspond to the premixed combustion phase became initially reduced and kept unchanged. With the increasing of biodiesel in the fuel blend, the HRR pattern was almost the same as that of conventional diesel, however it can be noticed that larger fraction of fuel was consumed during the mixing controlled combustion phase. This can be shown by the wider plateau after the first peak of HRR. In fact, this phenomenon can be observed clearly in the late SOI condition of 2°ATDC, in comparison with earlier SOI timing. The reason is that biodiesel has a greater cetane number than that of baseline diesel as depicted in Table 3. This causes ignition delay to be shortened, thereby producing a lower peak of HRR. In general, it is discovered that B20 and B50 combustion release 1.4 J/°CA and 4.3 J/°CA, respectively lower in HRR peak compared to baseline diesel over the entire range of SOI timings.

Effects of biodiesel blends, injection timing and split injection scheme on peak mean gas temperature (PMGT) and peak heat release rate (PHRR) are discussed in the following section. Fig. 7 shows the changes in PMGT with various SOI timings and split injection strategies of the engine operated with B20, B50 and baseline fuel. The PMGT of B20 and B50 are always found lower than that of baseline diesel over the entire range of SOI timings. Indeed, the results show that the highest PMGT of baseline diesel, B20 and B50 are 1964 K (at SOI = −12°ATDC), 1922 K (at SOI = 2°ATDC) and 1955 K (at
SOI = \(-12°\)ATDC respectively and with single injection scheme. Besides, it is observed that SOI timing variation profoundly influences the magnitude of PMGT. For single injection scheme, when SOI timing is set earlier, the PMGT will increase for all fuel type tested. The incremental effect is due to the higher peak combustion pressure, which results in a higher PMGT. However, for the corresponding SOI timing, there is a continuous reduction of the PMGT by an average of 5.1% and 9.3% for the case of double and triple injection, respectively, as compared to those of baseline diesel single injection operation. Another observation is that when triple injection scheme is implemented at SOI of \(-12°\)ATDC, it is found that PMGT decreases with biodiesel blended fuels. Another important combustion characteristic is the magnitude of PHRR. According to Fig. 7, it can be seen that B20 and B50 are consistently exhibit lower PHRR compared to baseline diesel for all SOI timings and injection schemes, except for the single injection operation. This is because biodiesel has a greater cetane number in comparison with baseline diesel. Consequently, biodiesel has a shorter ignition delay and a smaller peak of HRR, as aforementioned. Also, it can be seen that for a specific SOI timing, the PHRR is decreased with the increasing in number of split injections for all fuels. By diving the main fuel injection into two and three parts may reduced the quantity of fuel combusted in the premixed burn stage, thus lower PHRR.

Multiple injections approach, comprises pilot and post injections are commonly used to mitigate particulate matter/ smoke, controlling amount of NOx, managing engine combustion noise and to handling exhaust pipe after treatment equipment in diesel engine. Combustion pressure and heat release rate data of (a) single, (b) double, (c) triple injection at different SOI timings using baseline diesel as fuel can be obtained from Fig. 8. The beneficial effect of double and triple split injections will be discussed in this section by directly comparing different injection strategies with the corresponding SOI timing. This allows one to point out the differences in the combustion events that are responsible for results observed in NOx and smoke emissions. First, the double injection at later SOI of \(2°\)ATDC is compared to the single injection with similar injection timing in order to further analyze the benefits of one injection interruption. The heat release data shows that the two combustion events start deviating once the first fuel pulse of the double injection has been terminated after a premixed burn of about the same intensity, as can be clearly seen in Fig. 5. For double injection, as larger amount of the injected fuel has already been consumed in the premixed flame. Thus, the following combustion process during the injection dwell (i.e. the duration between the SOI_1 and SOI_2 as depicted in Fig. 5) is characterized by a fuel-air mixture that burns at very high temperatures. Consequently, the second fuel injection in double injection burns as a diffusion flame only. The fuel mixes with the hot gases remaining in the combustion chamber and ignites after a very short ignition delay. Besides, the double injection has a lower peak mean gas temperature that keeps the NOx production on a lower level, as shown in Fig. 7. The subsequent fuel injection causes another, slightly lower HRR and flame temperature rise, which lasts for about \(20°\)CA in the combustion cycle and ensured lower NOx production. Further optimization of split injections in terms of NOx and smoke emissions can be accomplished by using additional injection pulses, which is called triple injection. The experimental observation made by Pierpont found that the optimized triple injection, as the most sophisticated, but also most complicated injection strategy, can lower emissions beyond the capability of double injections [39,40]. The direct comparison of double and triple injection with the same injection timing as shown in Fig. 5, reveals that the two combustion events resulting from these strategies differ only in the second half. This combustion phase is most responsible for overall smoke emissions. The fuel combustion of the third injected fuel during piston expansion cooling stroke can be used to ensure a proper oxidation of the fuel-air mixture. This positive effect of the soot oxidation during the last stage of the combustion process can be noticed with the lower smoke emission level compared to the double injection, as is reflected in Fig. 4 with the late SOI timing of \(2°\)ATDC. Another interesting observation is that because of the similarity of the second and third fuel injection event, it is no surprise that the second and third peak HRR are almost identical for triple injection case (see Fig. 8c).

4. Conclusion

In the present study, the engine performance, combustion, and exhaust gas emissions characteristics of baseline diesel, B20 and B50 biodiesel blended fuels have been empirically tested in a medium-duty common-rail DI diesel engine. By holding the engine speed at 2000 rpm and at 60 Nm load as experimental condition, investigation of the effect of SOI timing and multiple injection strategies had been successfully carried out. Below are the main conclusions which are inferred from the present work.

(i) The diesel engine emissions, performance and combustion characteristics are affected by SOI timing and split injection scheme significantly for all types of fuel tested.

(ii) A considerably lower level of NOx, which is below 100 ppm, can be attained by retarded SOI timing for B20 and B50 fuel operations and with triple injection scheme.

(iii) Simultaneous NOx and smoke emission decrement from the
baseline levels of petroleum diesel fuel can be achieved by utilizing B50 in conjunction with implementation of retarded SOI timing and employment of triple injection scheme in a diesel engine. (iv) Multiple split injections is a practical strategies to simultaneously decrease NOx and smoke emissions when the SOI timing is fine-tuned and is an ideal alternative to operate with biodiesel fuel.

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References