Combustion Characteristics, Emissions and Engine Performances of a Split Injection Diesel Engine Fueled with Biodiesel Blended Fuels

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ABSTRACT

Biodiesel can be fueled in compression ignition (CI) engine to substitute fossil diesel. However, the substitution of biodiesel in CI engine can increase the emissions of CO, NOx, HC and smoke. In the present study, the consequences of biodiesel addition, SOI timing and number of fuel injections on engine out responses of the diesel engine are investigated. Variation of the start of injection (SOI) timing and a number of fuel injections using 20% and 50% of biodiesel mixing ratios were carried out at a constant speed and load. The results showed that a significantly lower NOx level can be attained by retarding SOI timing for both of the biodiesel blended fuels and with a higher number of injection pulse. Interestingly, with B50 fuel operation, the concurrent decrement of NOx and smoke by an average of 12% and 37%,

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respectively, in comparison to the corresponding baseline diesel can be attained with late SOI and triple injection strategy. With optimum SOI timing setting, the splitting of fuel injection into multiple events can be used to address NOx-smoke trade-off in a CI engine in conjunction with the operation of biodiesel fuel.

Keywords: *SOI Timing; Emissions; Combustion; Diesel Engine: Biodiesel*

Introduction

Recently, majority studies in CI engines are comparing diesel and biodiesel. Biodiesel fuel has a higher cetane number (CN), does not contain sulfur and aromatic contents, renewable and biodegradable [1]. Biodiesel can be produced from plant oil, animal fats and waste cooking oil [2]. In general, the use of biodiesel in CI engine significantly reduces the emission of unburned – hydrocarbon (HC), carbon monoxide (CO) and soot compared with fossil diesel fuel, but with a trade-off of increases in both of the NOx and brake specific fuel consumption (BSFC) [3, 4]. The increase in the formation of NOx is due to the oxygen content in biodiesel. The increased in oxygen level causes excess hydrocarbon oxidation, which leads to high local combustion temperature and increases the maximum temperature of combustion. The increase of BSFC of biodiesel is due to its higher density and lower calorific value [2, 5]. Through fuel modification only, the target of reducing NOx emission seems difficult to be achieved. Therefore, adjustments in engine operating parameters such as injection strategies and exhaust gas recirculation (EGR) are implemented to compensate for the difference between biodiesel and diesel in combustion characteristics.

Injection parameters such as fuel injection timing, rail pressure and pulse duration play a very important role in a diesel engine. Various studies have indicated that injection timing retardation reduces NOx emissions [6-9]. This is because retarding the injection timing reduces the maximum combustion temperature and pressure in the cylinder and hence decreases the formation of NOx. On the other hand, the emission of HC and CO decreases with advanced injection timing. A study performed by Agarwal et al. [10] on the impact of fuel injection timing on emissions and performance characteristics of a single cylinder CI engine using diesel. The results showed that both HC and CO emission decreases, but NOx emission increase significantly with advanced injection timing. Park et al. [11] also reported with advancement in injection timing, both HC and CO emissions reduced significantly.

Split injection strategies have been proven to reduce the CI engine emission [12, 13]. In a typical split injection used in CI engine, the pilot injection can help to reduce the engine noise and NOx emissions [14]. The main injection with a fully open needle (rectangular shape) or boost type shape will also reduce NOx emissions and post-injection reduce the soot emissions [15, 16]. Zhuang et al. [17] investigated the effect of split injection strategies in multi-cylinder CI engine. In this study, various fuel injection parameters of main injection timing, pilot injection quantity and timing as well as post-injection quantity and timing have been investigated. They reported early pilot injection with retarded main injection reduces NOx emissions and combustion noise while retarded main injection with post-injection reduces NOx and soot emissions. However, injection quality and timing have to be controlled precisely.

From the literature search and discussions, it can be seen that information about the influence of biodiesel blends in the engine equipped with split injection, in particular involving with multiple fuel injections of same quantities within a firing cycle was very limited. Thus a research gap remains in these topics which are investigated in this work.

Apparatus and engine testing procedures

This study was conducted using 3 fuel samples including petroleum diesel, B20 and B50 of coconut methyl ester blends. The experimental setup is the same as that described in How et al. [18]. A fully instrumented four-cylinder common-rail turbocharged diesel engine was directly coupled with an eddy current engine dynamometer to hold the engine speed and torque. An in-line volumetric fuel flow meter was used to measure the fuel supply to the engine. Multiple K-type thermocouples were employed to measure the temperature of room air, tailpipe gas, engine oil and water coolant. Table 1 listed the specifications of the test engine.

Table 1: Technical data of the test engine.

Type	Diesel, 4 stroke, turbocharged, Direct injection
Fuel supply system	Common-rail (1400 bar max.)
Cylinder	4
Valve for each cylinder	2
Bore x stroke	76.0 x 80.5 mm
Con. rod length	135 mm
Displacement	1.461 L
Compression ratio	18.25 to 1
Peak power and torque	48 kW (4000 rpm) and 160 Nm (2000 rpm)

In the present study, a commercially available microcontroller was used as a fuel injection controller unit. A total of three interrupt service routines were employed to pick up the signal from the incremental encoder and engine camshaft. To enable real-time fuel injection (i.e. pulse-width, SOI, and injection mode) control and engine parameters adjustment and monitoring, a LabVIEW graphical programming was employed in this study.

To characterize the combustion process, the pressure of cylinder was ascertained with a Kistler 6058A sensor and its signal was recorded with a high-speed data acquisition (DAQ) system. A custom fabricate glow plug adapter was used to mount the pressure sensor in the cylinder head of the first piston. Because the charge produced by the pressure sensor is very small, thus a charge amplifier was installed to amplify the charge signal. The resolution of the crank angle measurement was set to 0.125 °CA. In each run, combustion pressure data for hundred successive cycles were measured and averaged. Figure 1 presents the schematic diagram of the experimental arrangement. For the analysis of exhaust gas, an AVL DICOM 4000 gas analyser was employed to analyse the relative amount of NO_x. The opacity of smoke measurement was continuously measured using an AVL DiSmoke 4000 analyser.

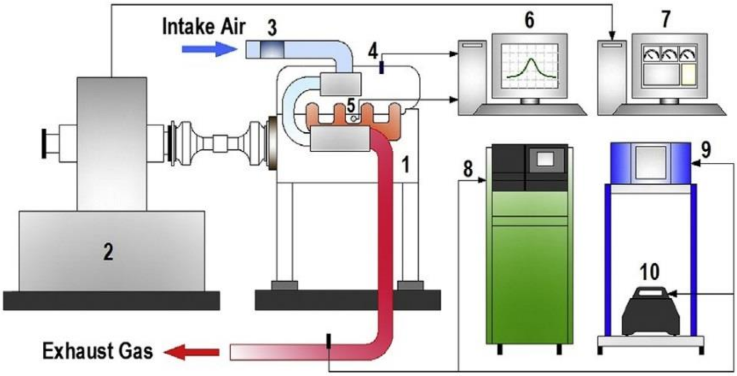

Figure 1: Arrangement of the experimental setup. 1. Multi-cylinder engine; 2. Dynamometer; 3. Air-Mass flow sensor; 4. Pressure sensor; 5. Accelerometer; 6. DAQ system; 7. Controller; 8. Bosch gas analyser; 9. AVL gas analyser; 10. Smoke opacity meter.

Engine operating condition

In this study, the engine testing is carried out at a constant speed and torque of 2000 rpm and 60 Nm, respectively. The effect of mixing of biodiesel fuels on engine-out responses under different injection mode (up to 3 equal injection pulses) and SOI timing (-12° ATDC to 2° ATDC) was investigated. Dividing the conventional main single fuel injection in modern diesel engine into multiple injection pulses of approximately equal size will help to reduce the flame temperature and enhance air-fuel mixing to improve charge homogeneity. Figure 2 shows the schematic diagram of the various injection strategies studied in this work. Clearly, the proposed strategies dissimilar in the main injection splitting schematization. For a conventional single injection technique, fuel supply into the cylinder was established by a single injection pulse. In the other injection mode, the fuel injection was established by twin injection, while in the third one by 3 identical injection pulses.

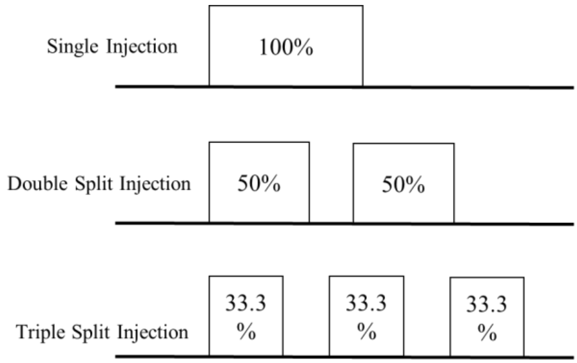

Figure 2: Various pattern of split injection strategies.

In each test programme, the comparison has been made with baseline fossil diesel fuel. Furthermore, the engine ran satisfactorily throughout the entire test even with biodiesel blended fuel, which was carried out at ambient temperature and had no problems with starting. All engine testing was carried out under steady-state conditions with an adequately warmed exhaust gas and coolant temperature. The main physicochemical properties for all fuels are given in Table 2. To improve the accuracy of the measurement, each run was reiterated two times to obtain average values. The repeatability is matched over 95% for each test.

Table 2: Main physicochemical properties of all test fuels.

Parameter	Units	Diesel	B20	B50	Testing standard
Calorific Value, MJ/kg	MJ/kg	45.21	44.6	42.79	ASTM D4809
Density @ 40°C	kg/m^3	825.6	831.3	840.1	ASTM D7042
Kinematic viscosity @ 40°C	mm^2/s	2.985	3.204	3.491	ASTM D7042

Results and Discussions

Performance characteristics

Figure 3 shows the results of BTE with variation in SOI and injection modes for all fuels. It can be seen that BTE of baseline diesel is consistently greater than that of B20 and B50 across all SOI timing. Also, the BTE is remarkably influenced by the alteration in SOI. There is a refinement in the BTE for all fuels with early SOI timings. This can be associated with the prolonged ignition delay that causing better fuel-air mixing, which in turn led to improving combustion and higher BTE. This phenomenon also can be explained by the early attainment of maximum pressure near to TDC with advanced SOI. As a result, a more useful work can be produced from the effective pressure developed [19]. However, for the same SOI setting, a progressively worsen in BTE for multi-injection operation can be observed in comparison to those of single injection operation for all fuels. This can be associated with the longer combustion duration for multi-injection operation. Consequently, the heat dissipation via the piston wall becomes greater, thus produced lower effective mechanical work. Another justification is that the power output is decreased because more fuel is burned in the expansion stroke and the cylinder pressure increases only when the cylinder volume is rapidly expanding, thus smaller effective pressure is generated. Besides, with a single injection operation at SOI of -12ºATDC, a lower BTE is found with higher biodiesel blend ratio. This observation also commonly seen in other SOI and split injection operation, which is well aligned with other studies [20, 21]. Besides, the higher oxygen content in biodiesel blend fuels also caused lower calorific value as indicated in Table 2.

From the BSFC results, it can be observed that both of the biodiesel blend fuels are constantly greater than that of baseline diesel across all SOI timings and injection strategies. A higher value of BSFC indicates that a greater amount of fuel was required for obtaining the similar power output and it is mainly due to smaller calorific value of B20 and B50 than that of baseline diesel. Also, it can be seen that the alteration in SOI has a greater effect on the changes in BSFC. With SOI advancement from 2° ATDC point, the BSFC reduced for all fuels. This reduction effect can be associated with the progressive improvement in the combustion efficiency and quality. With a fixed engine brake power output, the improving effect of the BSFC indicates less fuel is needed to operate the engine. This is especially for the case of early SOI timing. Furthermore, it can be seen that for the same SOI timing, the BSFC becomes greater with higher injection pulses across all fuels. This is in agreement with the result of [22, 23]. By splitting the fuel injection into multiple equal portions, the maximum combustion pressure became smaller, hence reduced the work done by the piston.

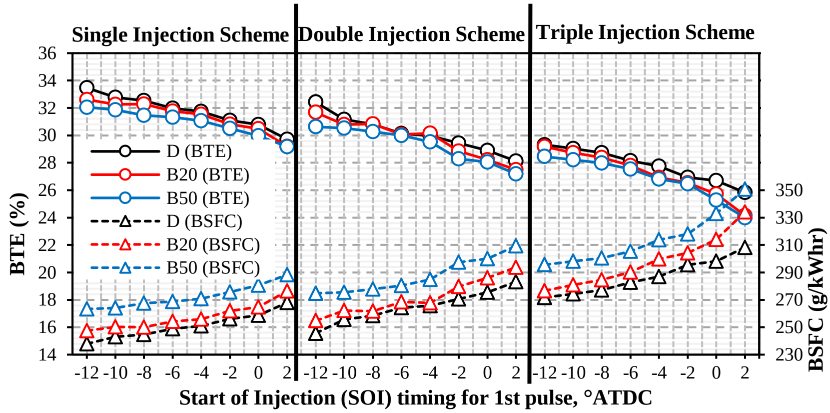

Figure 3: Experimental results of BTE and BSFC for all test fuels and engine testing condition.

Emissions Characteristics

As depicted in Figure 4 is the NOx emissions result for all fuels under different SOIs and split injection schemes. The general trend indicates that SOI advancement has resulted in higher NOx emissions for all fuels and injection schemes. The rising trend in NOx emissions proposed that with SOI advancement, the flammable mixture in the chamber explodes and burns earlier, hence the peak combustion takes place very close to TDC. Consequently, a greater combustion temperature is generated and thus stimulates the formation of thermal NOx. Besides, lower NOx emissions were observed for the case of biodiesel blended fuels across all SOIs and injection modes. This can be associated with the reduced rate of heat release at the premix phase and lower the combustion temperature. Furthermore, SOI retardation has resulted in NOx emissions of less than 100 ppm with both of the biodiesel blend fuels and with triple injection strategy. With retarded SOI, the combustion process is gradually retarded and moves away from TDC in the expansion stroke. Consequently, the combustion temperature is reduced and NOx formation is suppressed. Meanwhile, splitting the fuel injection into several equal portions reduced the NOx emissions. This can be explained by the division of heat release event into several sections and thus lowered the peak rate of heat release, thus lower the NOx formation. It is evidently showed that the split injection strategy is the effective method to decrease NOx.

The changes in smoke emissions for all fuels under different injection timing and schemes are depicted in Figure 4. The general trend indicates that the smoke emission reduced with the B20 and B50 across the entire SOI timings. This decrement effect than the corresponding data for diesel fuel can be related to the lower carbon content and higher fuel-borne oxygen in biodiesel blended fuels. The data also showed that with SOI advancement, the

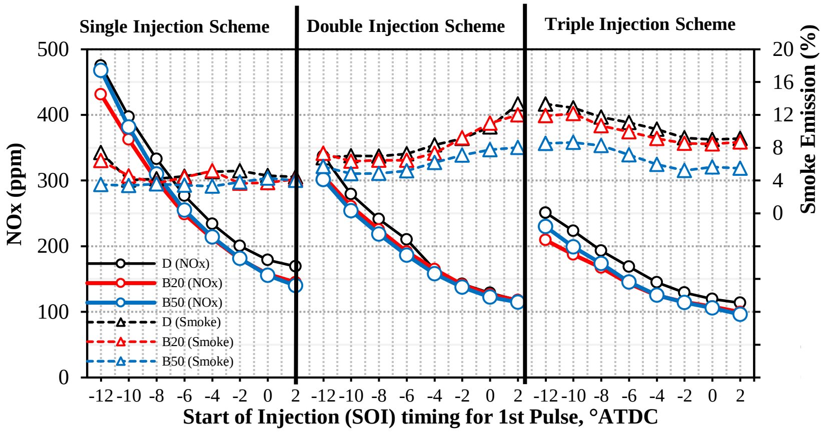

Figure 4: NOx and smoke emission for all operating conditions.

smoke emissions for double injection strategy were lowered and somewhat kept unvaried with the operation of a single injection scheme.

With advanced SOI, the operating temperatures in the cylinder are relatively high, which enhanced the oxygen to reacts with the fuel and led to lower smoke emissions for both of the injection strategies. Another explanation can be due to the fuel has relatively more and sufficient time for evaporation and mixing with air, resulting in more effective mixing and combustion. On the other hand, slightly higher smoke emission was observed with triple injection strategy and advanced SOI timings. The increment effect is due to reduced cylinder combustion temperature that led to a decrease in the burning rate, which causes incomplete combustion and increased smoke emissions. This indicates that a split injection can potentially cause higher smoke emissions if the SOI is not well-tuned. With higher biodiesel blend of B50, it is feasible to lower the smoke emission while still retaining the same decrement in NOx. In fact, the results also signify that about the same level of smoke emission (i.e. lower than 6% for diesel operation with single injection strategy) can be possibly achieved with B50 and combined with late SOI and triple injection. Another interesting trend can be observed is that a concurrent decrement of NOx and smoke by an average of 12% and 37%, respectively, compared with the respective baseline diesel can be attained with late SOI and triple injection strategy. Therefore, concurrent NOx and smoke decrement from the case of fossil diesel is feasible with the implementation of B50 fuel, retarded SOI, as well as with triple injection scheme. As shown in Table 3 is the summary of quantitative results of NOx and smoke emissions reduction achieved with the implementation of various strategies of biodiesel blend, SOI timing alteration and split injection strategy. Although the strategy number 2 can lead to the simultaneous NOx and smoke reduction, however, the strategy number 7 is much promising as it includes the effect of biodiesel toward the effort of reduction of both of the emissions.

Table 3: Comparison of the variations on exhaust emissions of NOx and smoke with various potential emissions reduction strategies.

No	Strategy			Percentage change (%)		Fixed parameter
	Biodiesel blend	SOI timing variation	Split injection	NOx	Smoke	
1	√	-	-	↓(-8)	↓(-24)	Diesel vs B50 @ nominal SOI = -6°ATDC
2	-	√	-	↓(-181)	↓(-66)	Late SOI=2°ATDC vs advanced SOI = -12°ATDC with Diesel & Single injection
3	-	-	√	↓(-39)	↑(+146)	Single vs triple injection @ nominal SOI= -6°ATDC & with Diesel
4	√	√	-	↓(-17)	↓(-52)	With single injection
5	√	-	√	↓(-48)	↑(+58)	At nominal SOI= -6°ATDC
6	-	√	√	↓(-47)	↑(+80)	With diesel fuel
7	√	√	√	↓(-80)	↓(-30)	Compare to SOI= -12°ATDC, Diesel fuel & single injection

Characteristics of Combustion Process

To investigate the influence of different injection scheme and biodiesel blends on the combustion process, the cylinder pressure for 100 successive firing cycles were sampled, averaged, and analysed. Figure 5 demonstrates the result of combustion pressure, HRR and injector current profile for engine operation with baseline diesel at SOI of -6°ATDC (nominal case) and with three types of injection scheme. From the plot of injector current waveform, it can be found that the fuel injection event was resulted by two and three equal injection pulses for double and triple injection approaches, respectively. Furthermore, the results also show that engine operation with split injection schemes gives a remarkable influence on the combustion process. The occurrence of pressure peak happened earlier in the compression stroke with the higher pulse of fuel injection. Meanwhile, the crank angle position of the start of combustion (SOC) timing for double and triple injection was happened earlier by 0.5°CA and 1°CA, respectively than the case for a single injection. Besides, a slight pressure peak reduction of approximately 1.7 bar was observed for a double injection operation. On the other hand, engine operation with a triple injection scheme has resulted in a small rise in the pressure peak of approximately 1 bar. Two and three remarkable peaks of HRR were noticed for double and triple injection schemes, respectively. Meanwhile, it can be evidently seen that the crank angle occurrence for the first peak of HRR was happened earlier by 0.5° CA and 1° CA for double and triple injection strategy, respectively, compared to single injection strategy. This can be attributed to the advance in SOC timing, which resulted in the earlier rise in the HRR. In addition, the two diffusion combustion resulting from the successive fuel injections happen at about the same moment after the start of injection for both timings (ignition delay_2 is about the same with ignition delay_3) but the lower magnitude is clearly seen. The second and third fuel pulse burn almost instantly, well after the SOI_2 and SOI_3 because the injected fuel is directly penetrated into the main combustion regions.

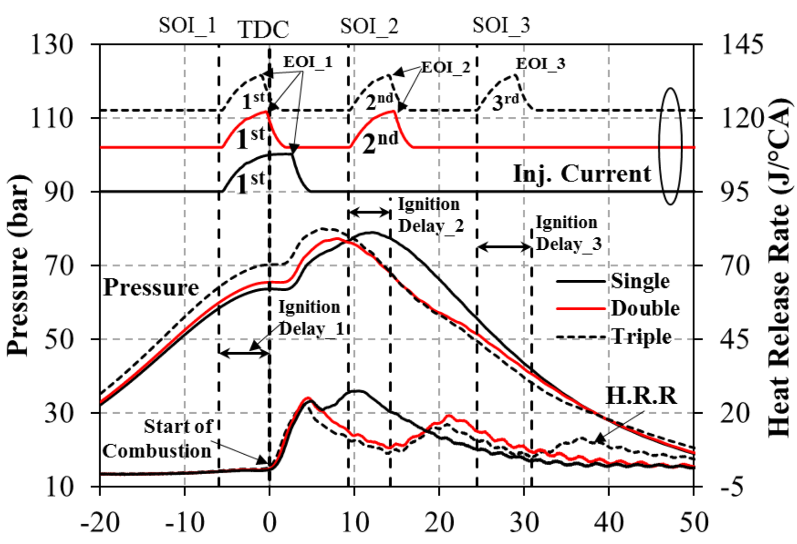

Figure 5: Combustion pressure, HRR and injector current signals for baseline diesel with different injection scheme at SOI of -6°ATDC.

Conclusion

The results obtained from the experiments are summarised as follows:

i. Variation in SOI timing and split injection scheme have a remarkable influence on the engine performance, emissions and combustion characteristics for all tested fuels.
ii. NOx emissions of less than 100 ppm can be obtained by late SOI for both of the biodiesel blend fuels and with triple injection strategy.
iii. The concurrent decrement in NOx and smoke can be attained with late SOI and triple injection strategy.
iv. Split fuel injection technique has been proven to be a feasible solution to simultaneously reduce smoke and NOx emissions when the injection timing is well-tuned and is a promising strategy to operate with biodiesel fuel.

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