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# Experimental study on combustion characteristics of an indirect injection diesel engine fuelled by biodiesel blends

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**Abstract.** An experimental investigation was conducted to evaluate the performance of an indirect injection (IDI) diesel engine using diesel (D100) and diesel-biodiesel blends (BD25, BD45, BD65) separately. The engine was run in various engine loads at constant engine speed ranging from 1000 to 2400 rpm with an interval 200 rpm. The results showed that the maximum pressure inside a cylinder of D100 is slightly higher than that of BD65 and other biodiesel blends. The biodiesel blends exhibited higher pressure change rate at a moment before peak pressure inside the combustion chamber. It was also clearly observed that the heat release rate of D100 is higher than those of biodiesel blends. This result is consistent with the higher engine power delivered by D100 compared to the biodiesel blends. In related to the combustion period, it was recorded that BD65 started the combustion slightly earlier than that of D100. This resulted in the shorter ignition delay of BD65 compared to D100. On the other hand, from the burnt mass data it was found that the BD65 ended the combustion later than the D100. This means the combustion duration of biodiesel blends are longer than that of diesel fuel which is worse combustion condition.

## 1. Introduction

The prospect of the use of biodiesel to replace fossil fuels has received much attention since the past decades. Beside its ability as an alternative for diesel fuel in engine performance side, the environmental-friendly properties of biodiesel also encouraged the use of biodiesel. The term biodiesel commonly refers to fatty acid methyl or ethyl esters made from vegetable oils or animal fats, whose properties are good enough to be used in diesel engines [1]. There have been many reports on the effect of biodiesel on diesel engine performance. The results of these works are sometimes quite diverse and even contradictory. For example, when the most of reports showed that the use of diesel and biodiesel blend decreased the engine power, Altiparmak et.al [2] reported the increases in power and torque when using a blend with 70% biodiesel. Lapuerta et.al [3] conducted a massive review on the effect of biodiesel on diesel engine emissions with an enclosed brief review on the engine performance and showed varied results on the engine performance and emissions. The lower LHV of biodiesel compared to diesel fuel got much attention in the engine performance analysis. Meanwhile, the role of the cetane number and diesel engine type had less attention. In more specific biodiesel type, Enweremadu & Rutto [4] reviewed the effect of used cooking oil biodiesel on combustion, emission, and engine performance characteristics. In spite of that, relatively high disparity results were still found especially for emission characteristics. More recently Xue et.al [5] conducted a similar review and still reported inconsistent trends for biodiesel engine performances and its emissions due to the different tested engines, the different operating conditions or driving cycles, the differently used biodiesel or reference diesel, the different measurement techniques or instruments, etc. The comparison with other reports in such review paper [3-5] gave valuable insight into the role of fuel properties to the engine performance and emission characteristics.

In relation to the following review to other reports, we gave deeper attention to the diesel engine type (i.e. DI or IDI), and three fuel properties i.e. fuel density/viscosity, fuel Cetane number, and fuel



heating value to get a more comprehensive explanation on the contribution of these parameters to engine performance characteristics. The higher density and viscosity of biodiesel will have an effect to fuel compression process in the injection pump i.e. causes faster increase to reach the nozzle opening pressure. As a result, this can cause an advance injection and/or ignition timing. This also causes poor atomization compared to lower density fuel. The higher density and viscosity will also result in longer spray tip penetration and lower spray cone angle that is important in DI than IDI diesel engine. Cetane number is a measure of ignition quality. Cetane number is actually a measure of ignition delay. Higher cetane number will have a shorter ignition delay that will improve the combustion process. Higher cetane numbers indicate shorter times between timing of injection and ignition of the fuel [6]. The different type of biodiesel may have higher or lower cetane number compared to diesel fuel. Biodiesel generally has oxygen content around 10% to 12% compared to zero oxygen content in diesel fuel. The oxygen content in the biodiesel has two impacts; *firstly*, lowered the fuel heating value; and *secondly*, improved combustion by providing more complete combustion. The lower heating value of the fuel is a very important property that is related to the available energy in the fuel. Biodiesel generally has lower LHV, higher density, and viscosity, but may have higher or lower cetane number compared to diesel fuel. These fuel properties may come contrarily into the biodiesel, so it is important to give more attention to assess the overall effect of these properties to the combustion process.

As for engine type, it is important to distinguish DI and IDI diesel engine because of the difference in nature of the air-fuel mixing in the combustion chamber. In an IDI diesel engine, air is pushed into the swirl pre-chamber on the cylinder head by the piston and starts swirling rapidly, which promotes a good mixing when the fuel is sprayed. This makes a better mixture of the air and fuel, which improves combustion. Preliminary combustion of the mixture starts and heat rises, forcing the remaining unburned fuel into the chamber at high velocity, where it mixes well with the air and continues the complete combustion [7, 8]. In the indirect injection combustion process, air-fuel mixing is more important. Meanwhile, in a direct injection system, fuel is introduced directly into the combustion chamber, and as a result, the fuel spray characteristics have a bigger contribution to improve the combustion.

The decrease of torque was reported by most of the authors [9-14] for IDI and [15-22] for DI diesel engines with all mentioned the lower LHV of biodiesel as the main cause. Laforgia and Ardito [9] used IDI diesel engine and neat rapeseed biodiesel with 5.1% higher density and 12.9% lower LHV compared to those of the diesel fuels but with a higher cetane number of the biodiesel in their experiment; and reported the decrease of torque at level 2%. Ryu and Oh [10-11] showed similar results when used biodiesel with 5.1% higher density, 14.6% lower LHV, and higher of cetane number of biodiesel in an IDI diesel engine; and the results showed a slight decrease of torque with BD100. A relatively bigger decrease of torque occurred for biodiesel with significant lower both cetane number and LHV compared to that of diesel fuel are presented by Cetin & Yuksel [12] that used hazelnut oil with 5.8% higher density, 27.2% lower LHV, and lower cetane number of biodiesel in an IDI diesel engine and reported around 7% decrease of the torque with BD100. Similarly, Buyukkaya [21] reported a 4.9% decrease of torque when using BD100 in DI diesel engine with 9.9% higher density, 14.4% lower LHV, and lower cetane number, respectively. The lower cetane number of biodiesel might result in the much worse combustion as shown in the higher decrease of torque. It is difficult to find the difference of the torque resulted by DI and IDI diesel engine since both showed a different level of the decrease due to the difference in LHV and cetane number.

The reduced of power was reported by the most of authors [9-12, 23] for IDI and [15-22, 24-25] for DI diesel engines in various level of decrease with all mentioned the lower LHV of biodiesel as the possible cause. There is an exception result from Altiparmak et.al work [2] that reported the increase of power when using very high density of biodiesel ( $922 \text{ kg/m}^3$ ; compared to  $835 \text{ kg/m}^3$  of the diesel fuel) and higher cetane number of biodiesel (54; compared to 43.76 of the diesel fuel). Similar to the torque, the bigger power decrease is found in the present study and Cetin and Yuksel [12] and Cetinkaya et.al [16] when the lower LHV and lower cetane number of biodiesel to be present together in the biodiesel. Cetin & Yuksel [12] reported the power decrease up to 15% while Cetinkaya et.al

[16] reported the decrease up to 9% when using hazelnut oil and used cooking methyl esters, respectively. In the reports mentioned above the level of power, decrease varied strongly from almost no difference to less than 8% compared to the diesel fuel.

In related to brake-thermal efficiency, some authors noted the increase when using biodiesel blends in IDI engine [9, 13, 26] and DI engine [21, 27]. The possible reasons for the increase of brake thermal efficiency are better combustion due to the additional oxygen content [13, 26] and better-improved lubricity by the biodiesel content [21, 28, 29]. Rakopoulos et.al [27] reported the increase of brake thermal efficiency for medium load and inconsistent trend for high load, and this was down to the small uncertainty in the measurements of the fuel heating value and consumption rates. On the other hand, Ozsezen et.al [18] and Behcet [22] noted the decrease of brake thermal efficiency when using biodiesel blends. Ozsezen et.al [18] simply mentioned the higher brake specific fuel consumption and lower energy content; while Behcet [22] mentioned the longer ignition delay due to high viscosity and density of biodiesel that resulting in poor atomization and incomplete combustion as the possible reasons. In respect to the diesel engine type, generally, the DI diesel engine [18, 21] has higher thermal efficiency than the IDI diesel engine [9, 13, 26]. This is understandable since the IDI diesel engine has additional pre-chamber that enhanced the surface area and the heat loss.

The increase of the brake specific fuel consumption and the decrease of the brake specific energy consumption were reported by all authors of reviewed paper in the present study both in IDI [9-14, 26, 30] and DI [2, 17-19, 21-22, 24-25, 27, 31] diesel engine regardless of the cetane number of biodiesel lower or higher than the diesel fuel.

Several authors conveyed that the peak cylinder pressure by diesel fuel is higher compared to the biodiesel and its blends regardless of the cetane number and diesel engine type [12-13, 21, 30-32] and explained the higher energy supplied by diesel fuel as the reason. Some other authors reported that biodiesel and its blends resulted in higher peak pressure than the diesel fuel in spite of the power decreased with the biodiesel blends [9-11, 18]. Ryu and Oh [10-11] mentioned the contribution of oxygen, while Laforgia [9] stated as the worse combustion due to the longer ignition delay and combustion duration. Ozsezen et.al [18] described the higher BSFC amount, higher cetane number, oxygen content and advanced of the start of injection timing as the reasons. As a note, in all those reports [9-11, 18] the cetane number of biodiesel is higher than that of diesel fuel. Sahoo and Das [33] reported in their work that biodiesel and its blends from *Jatropha*, *Karanja*, and *Polanga* resulted in higher peak cylinder pressure without information on the cetane number and engine power.

Several authors proved that biodiesel resulted in an earlier start of combustion compared to diesel fuel regardless of the value of cetane number [9-11, 18, 21, 31]. It seemed caused by higher density and viscosity that affected faster pressure increase in fuel delivery and faster injector opening time.

In related to the emission, by Altiparmak et.al [2] reported that NO<sub>x</sub> increased up to 30% when using biodiesel blends. However, several reports showed a lower increase at around 6%-10% [21, 22, 25]. In related to smoke opacity, another main pollutant from biodiesel, some reports showed the small decrease of smoke opacity at around 10%-25% [13, 22, 29], while some authors reported the decrease of smoke opacity with the biodiesel contents reached 30%-46% [2, 11, 21].

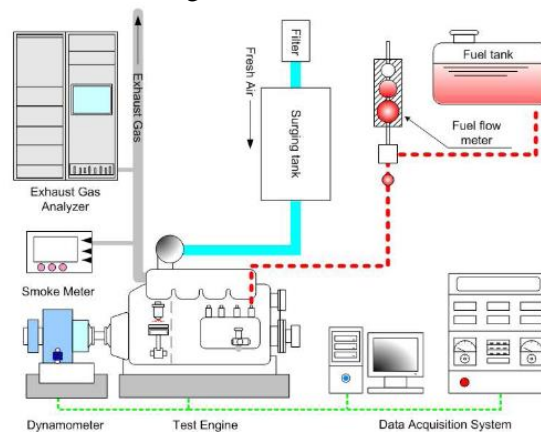
In the present work, the blend of biodiesel derived from soybean oil would be tested in an IDI diesel engine. The additional raw material like waste edible oil or animal fats might be mixed to meet the biodiesel standard in Korea. The objective of this work is to investigate the combustion characteristics compared to standard diesel fuel. The data resulted from this work would be discussed and compared to other reports with giving more attention to the density, LHV, and cetane number of the biodiesel and diesel engine type and its role to the engine performance.

## 2. Experimental setup

The experiments were conducted on three cylinders, four-stroke, natural aspirated indirect injection diesel engine. The schematic of the experimental facility is shown in Fig. 1. The engine specifications are shown in Table 1. The engine was connected to an engine dynamometer providing maximum engine power of 74 kW. The engine was tested at various engine load, fuelled with diesel and diesel-

biodiesel blends at constant engine speed ranging from 1000 to 2400 rpm with interval 200 rpm. At each speed of testing, the maximum torque of each fuel was recorded. The engine speed, torque, crankshaft position, and the cylinder pressure were recorded simultaneously into a computer connected to the engine dynamometer. The fuel consumption was measured by a fuel meter by recording the fuel delivered to the engine for a given time the engine operated. The exhaust gases produced from the diesel engine are then directed to a sampling pipe connected to the emission monitoring device MRU MGA5 during 5 - 10 minutes until the relatively constant value of NO<sub>x</sub> emission is reached. Another sampling pipe is used to be connected to opacimeter (OP-160) that monitors the smoke opacity of the exhaust gas.

The biodiesel used in this experiment was derived from soybean and waste edible oil produced by local producer. The diesel and biodiesel properties are shown in Table 2. At the engine running, the power, torque and engine speed were monitored and then recorded from 1000 rpm to 2400 rpm. The order of testing was firstly diesel fuel, then the blends of diesel and biodiesel with 65% (BD65), 25% (BD25) and 45% (BD45) in volumetric weight of biodiesel.



**Figure 1.** The experimental facilities

**Table 1.** Engine specifications

Item	Specification
Engine type	In-line, vertical, 4-stroke
Cylinder number	3
Bore, stroke, capacity	75 mm x70 mm, 927 cm <sup>3</sup>
Combustion system	In-direct, vortex chamber
Compression ratio	22: 1
Injection timing (BTDC)	24°
Injection pump	Bosch K type mini pump
Injection pressure	13.7 MPa
Injection nozzle	Throttle type

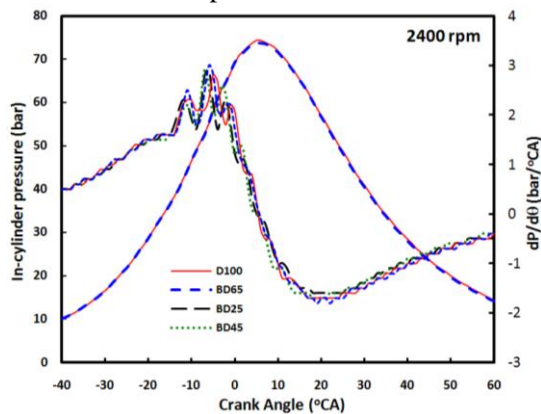
**Table 2.** Diesel and biodiesel properties

Fuel properties	Diesel	Biodiesel
Density (kg/m <sup>3</sup> )	850	882
Viscosity (mm <sup>2</sup> /s)	3.25	4.3
Flash point (°C)	68	177.9
Cetane number	54.6	54.2 ~ 58
LHV (MJ/kg)	43.15	39

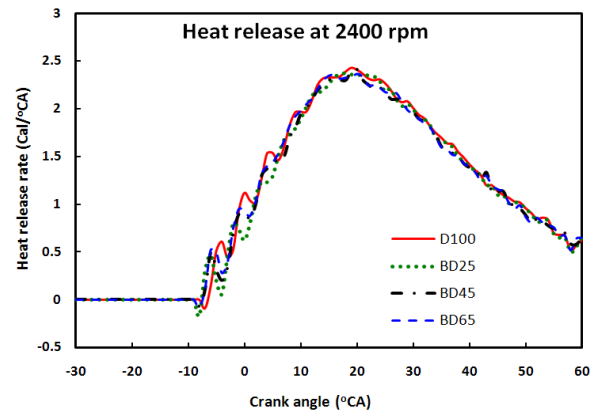
### 3. Results and Discussion

#### 3.1 Heat release rate

Figure 2 shows the variations of cylinder pressure with a crank angle for diesel fuel and BD65 at 2400 rpm. The pressure change rate in bar/°CA is also presented in the same graph. From this graph, it is shown that the maximum pressure inside the cylinder of D100 is slightly higher than that of BD65 and other biodiesel blends. This could be down to the higher energy supplied by diesel fuel. The cylinder pressure is deliberately shown only for D100 and BD65. The cylinder pressure for the BD25 and BD45 are between D100 and BD65. On the other hand, the biodiesel blends exhibited higher pressure change rate at a moment before peak pressure inside the combustion chamber. This could be considered as the role of the higher oxygen content in the biodiesel that improved combustion at the main combustion period.



**Figure 2.** In-cylinder pressure & rate of pressure change of D100 & BD65 at 2400 rpm



**Figure 3.** The heat release rate with respect to crank angle and fuel type at 2400 rpm

The heat release rates of all tested fuels are presented in Figure 3. It is shown that biodiesel blends started the combustion earlier than that of D100. From Figure 3 it is also observed that the heat release rate of D100 is slightly higher than those of biodiesel blends. This result is consistent with the higher engine power delivered by D100 compared to the biodiesel blends.

**Table 3.** Combustion parameters at 2400 rpm and full-load engine operation

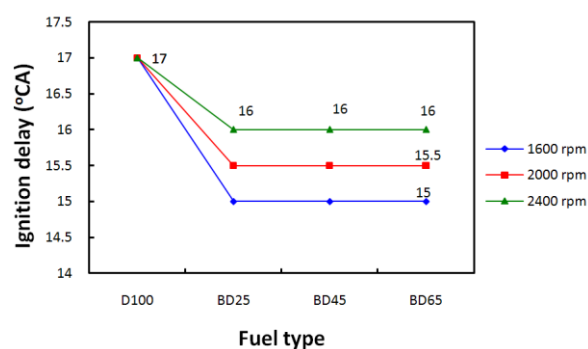
Fuel type	Max pressure (bar)	Start of injection (°BTDC)	Start of combustion (°BTDC)	Ignition delay (°)	End of combustion (°ATDC)	Combustion duration	Max heat release rate (cal/°CA)
Diesel	74.4	24	7	17	91	98	2.43
BD25	74.2	24	8	16	97	105	2.37
BD45	74.1	24	8	16	98	106	2.40
BD65	73.8	24	8	16	98	104	2.37

The related combustion parameters to the in-cylinder pressure and the heat release as shown in Figure 2 and 3 is shown in Table 3. The start of injection is assumed same with the engine's manufacturer specification, while the start and end of combustion are decided from heat release and burnt mass data. The maximum pressure resulted by D100 is 74.4 bar, slightly higher than 73.8 bar of BD65. However, the maximum heat release rate of D100 is higher than that of BD65. In related to the combustion period, it was recorded that BD65 started the combustion slightly earlier than that of D100. This resulted in the shorter ignition delay of BD65 compared to D100. On the other hand, from the burnt mass data we found that the BD65 ended the combustion later than the D100. This also occurs with

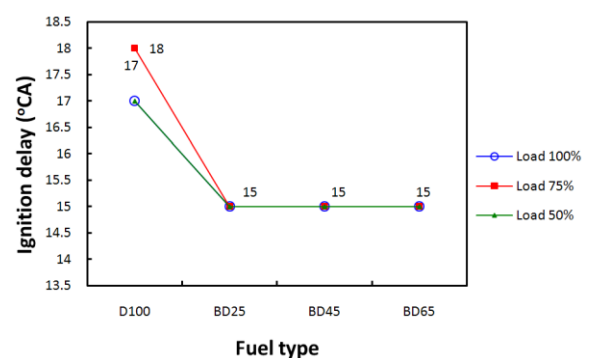
other biodiesel blends. This means the combustion duration of biodiesel blends are longer than that of diesel fuel which is worse combustion condition. It suggested that the higher density and viscosity of biodiesel played its role in faster-increasing pressure in the fuel line caused the earlier start of combustion, and on the other side resulted in poor atomization and slower fuel-air mixing.

### 3.2 Ignition delay and combustion duration

Figure 4 and 5 show the ignition delay of the tested fuels at various engine speed and various engine load (at constant 1600 rpm), respectively. It is clearly observed that the biodiesel blends have shorter ignition delay compared to those of diesel fuel, with no difference between biodiesel blends. The ignition delay increased slightly with the increase of the engine speed as a consequence of more fuel injected that resulted in a longer time to break into droplets and its chemical readiness to be burned. From Figure 5 it can be said that the ignition delay doesn't change due to the engine load.

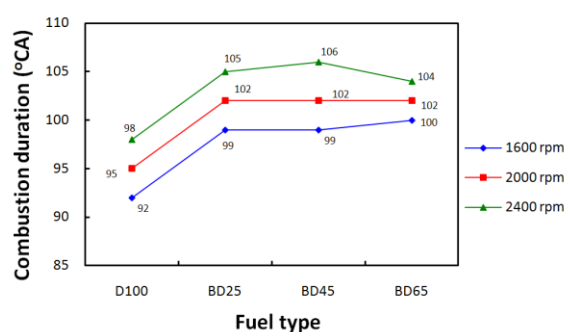


**Figure 4.** The ignition delay at various engine speeds with the fuel type

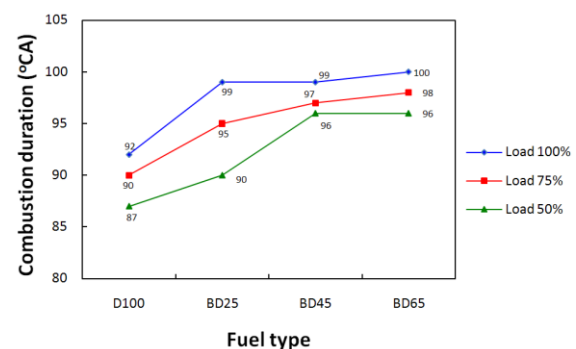


**Figure 5.** The ignition delay at various engine loads with the fuel type

The combustion duration of the tested fuels at various engine speed and various engine load (at constant 1600 rpm) show similar phenomenon, as shown in Figure 6 and 7, respectively. The combustion duration increased with both the engine speed and load. As mentioned before, this might be caused by more fuel injected at higher engine speed. It is also clearly observed that the combustion duration of biodiesel blends is always longer than those of diesel fuel. This proved again the contribution of the higher density of the biodiesel fuel compared to the diesel fuel.



**Figure 6.** The combustion duration at various engine speeds with the fuel type



**Figure 7.** The combustion duration at various engine loads with the fuel type

## 4. Conclusions

The combustion characteristics of an IDI diesel engine fuelled with diesel and diesel-biodiesel blends were experimentally conducted. The results can be concluded as follows:

- a. The maximum pressure inside the cylinder of D100 is slightly higher than that of BD65 and other biodiesel blends. On the other hand, the biodiesel blends exhibited higher pressure change rate at a moment before peak pressure inside the combustion chamber. This could be considered as the role of the higher oxygen content in the biodiesel that improved combustion at a moment before the main combustion period.
- b. From the heat release analysis, it is found that the heat release rate of D100 is higher than those of biodiesel blends. The biodiesel blends started earlier and ended the combustion later than the D100. This means the combustion duration of biodiesel blends are longer than that of diesel fuel which is worse combustion condition.
- c. The biodiesel blends have shorter ignition delay compared to those of diesel fuel, with almost no difference between biodiesel blends. The ignition delay increased slightly with the increase of the engine speed as a consequence of more fuel injected that resulted in a longer time to break into droplets and its chemical readiness to be burned. The combustion duration increased with both the engine speed and load. The combustion duration of biodiesel blends is always longer than those of diesel fuel. This proved again the contribution of the higher density of the biodiesel fuel compared to the diesel fuel.

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