The Engine Performance Characteristics of an IDI Diesel Engine Fueled by Soybean Oil Methyl Esters

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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 biodiesel content decreased the engine torque and power. This might be mainly affected by the lower LHV of the biodiesel, and also the worse combustion due to higher density of the biodiesel compared to the diesel fuel. The loss of power due to lower heating value of biodiesel were not as high as the difference in their heating value that might be down to the better lubricity of biodiesel as proved in the higher brake thermal efficiency and mechanical efficiency when using the biodiesel blends. The brake specific fuel consumption is higher with the increase of biodiesel content but the diesel fuel delivered the highest energy to run the engine. The maximum pressure inside cylinder and the heat release rate of D100 is slightly higher than those of biodiesel blends.

Keywords: *diesel engine, biodiesel, engine performance, emission.*

I. INTRODUCTION

The prospect of the use of biodiesel to replace fossil fuels has received much attention since past decades. Beside its ability as 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 vegetables 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 the 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 decrease the engine power, Altipamark 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 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 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 a 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 different 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 on the role of fuel properties to the engine performance and emission characteristics.

In relation with 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 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 the 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 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 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 direct injection (DI) and indirect injection (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. A 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 the result the fuel spray characteristics has bigger contribution to improve the combustion.

The decrease of torque was reported by the most of 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 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 biodiesels in an IDI diesel engine; and the results showed a slightly 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 hazenut 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 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 biodiesels 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 difference level of 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 kg/m^3; compared to 835 kg/m3 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 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 biodiesels are 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.

In related to the emission, by Altiparmak et.al [2] reported that NOx increased up to 30% when using biodiesel blends. However, several reports showed 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 engine performance and its 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.

II. MATERIALS AND METHODS

The experiments were conducted on a three-cylinders, four-stroke, natural aspirated indirect injection diesel engine. The schematic of 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 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 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.

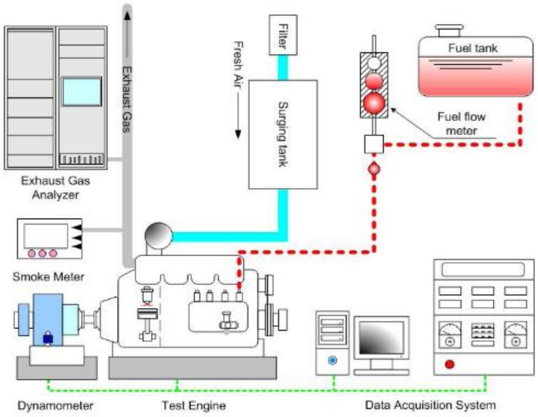


Figure 1. The experimental facilities

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^3
Combustion system	In-direct, vortex chamber
Compression ratio	22:1
Injection timing (BTDC)	24º
Injection pump	Bosch K type mini pump
Injection pressure	13.7 MPa
Injection nozzle	Throttle type

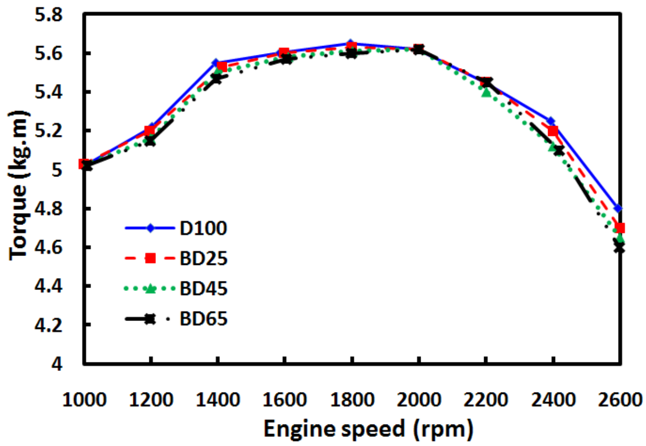
Table 2. Diesel and biodiesel properties

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

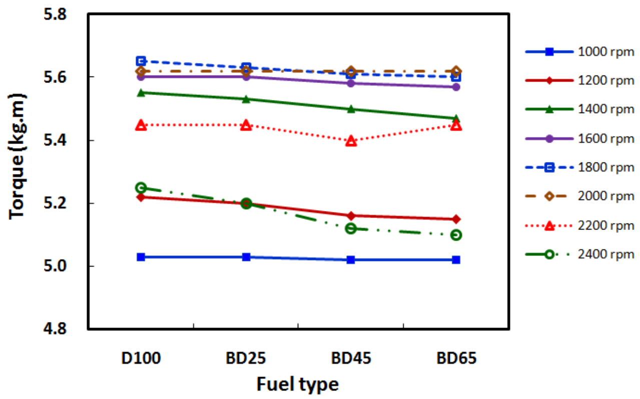
III. Results and Discussions

Fig. 2a and 2b show the graphical plot of the engine torque at full-load based on the engine speed and fuel type, respectively. The Fig. 2a and 2b show that the biodiesel content decreased the engine torque. The torque increases with the increase of engine speed until 1800 rpm, then decreases with the increase of engine speed. The maximum torque was reached at 1800 rpm for D100 and BD25; and at 2000 rpm for BD45 and BD65, respectively. The relative decrease of torque with biodiesel blends are up to 2%, 2.5%, and 4% for BD25, BD45, and BD65, respectively.

The neat biodiesel in the present study has 3.7% higher density, 14.5% lower LHV, and higher cetane number, respectively; compared to those of diesel fuel. These properties suggested both disadvantages and advantage impact to the performance. The lower torque reached in the present study might be mainly affected by the lower LHV of the biodiesel, and also the worse combustion due to higher density of the biodiesel compared to the diesel fuel. The higher cetane number of biodiesel seemed having less contribution to improve the combustion.



a. Torque at full-load with the engine speed



b. Torque at full-load with the fuel type

Figure 2. Variations of the torque at full-load

Fig. 3 shows the torque at engine speed 1600 rpm for various engine-loads. The torque decreases with the decrease of engine load as consequence of less fuel supplied to the engine. The decrease of engine torque due to the biodiesel content is more obvious at lower engine load; shown by the sharper decrease of the torque line at load 75% and 50%.

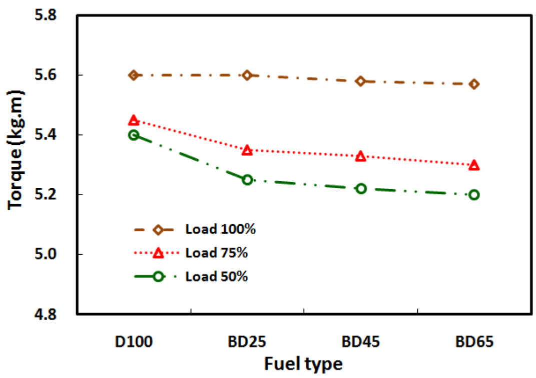
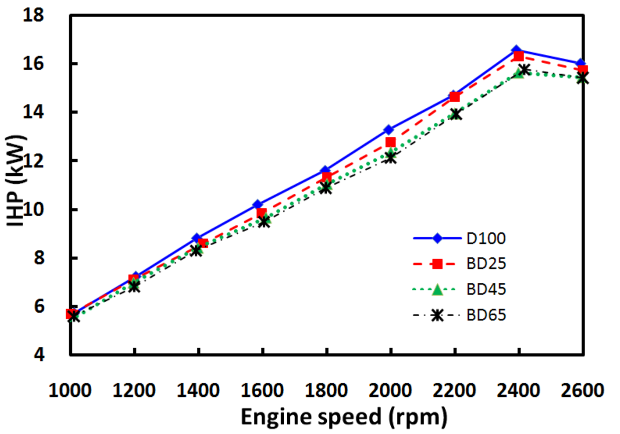
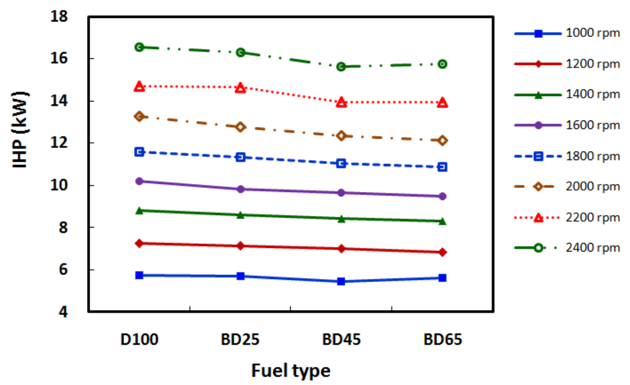


Figure 3. The torque at 1600 rpm for the various engine-loads with the fuel type

Fig. 4a and 4b show the graphical plot of the indicated horse power at full-load based on the engine speed and fuel type, respectively. Fig 4a and 4b show that the power increases with the increase of engine speed until 2400 rpm, then decreases with the increase of engine speed. It is also shown that the indicated horse power is slightly decrease with the increase of biodiesel content. The maximum power was reached at 2400 rpm for each fuel type. The indicated horse power reached by neat diesel fuel was still higher than the blends of diesel and biodiesel. This is understandable since the lower heating value of biodiesel is suggested to be responsible as the main cause for the torque and engine power decrease. The higher density of the biodiesel might also deteriorate the combustion. Further examination showed that the loss of power due to lower heating value of biodiesel were not as high as the difference in their heating value. For example, the LHV of BD65 is 9.2% lower than LHV of D100, however the indicated horse power of BD65 varied 2%-8.7% lower than that of D100 depend on the engine speed.



a. Indicated hp at full-load with the engine speed



b. Indicated horse power at full-load with the fuel type

Figure 4. Variations of the indicated horse power at full-load

The lower LHV of biodiesel might be the main possible reason, but should not be considered alone when evaluating the power decrease in diesel engine using biodiesel. Cetin and Yuksel [12] and Cetinkaya [16] found the power decrease up to 15% when using biodiesel with lower cetane number compared to that of diesel fuel. The difference of cetane number of the biodiesel could have contribution to the level of power decrease as well as the level of difference in density between diesel and biodiesel.

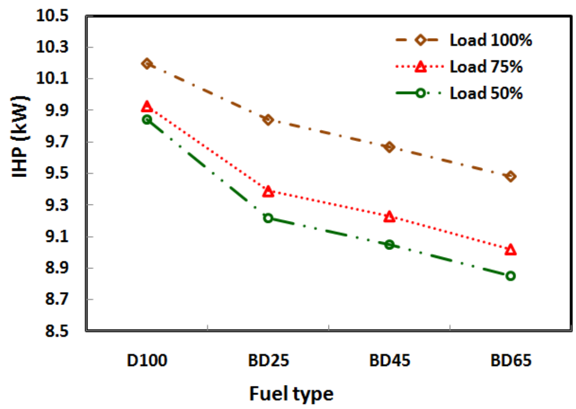


Figure 5. The IHP at 1600 rpm for the various engine-loads with the fuel type

Fig. 5 shows the IHP at engine speed 1600 rpm for various engine-loads. The IHP decreases with the decrease of engine load as consequence of less fuel supplied to the engine. The decrease of IHP due to the biodiesel content at load 75% and 50% seemed to be similar to that of full-load.

The better lubricity of biodiesel might be mentioned as reason to the power recovery in the present study. The better lubricity of biodiesel could come from the methyl esters content that enhance the biodiesel lubricity better than hydrocarbon [34-35]. As a note, the biodiesel used in the present study contains 98.1% weight of fatty acid methyl esters.

The role of the better lubricity of biodiesel could be seen from the brake thermal efficiency. As shown in Fig. 6, the brake thermal efficiency of the biodiesel blends fuel was higher than those of neat diesel fuel. The probable cause for this is the better lubricity provided by the biodiesel content in the fuel. As for the decrease of brake thermal efficiency since 1600 rpm, this might be caused by the lower air-fuel ratio at higher engine speed affected to the combustion in the engine. The better lubricity of biodiesel could be also observed from the mechanical efficiency as shown in the Fig. 7. The mechanical efficiency varied over the engine speed; and it is clearly that the fuel with biodiesel content has higher mechanical efficiency than that of diesel fuel. The mechanical efficiency is brake to indicated horse power ratio; that represents the energy loss in friction including in cylinder wall and piston parts [7, 8]. The better lubrication in the piston and cylinder would improve the mechanical efficiency. Several authors mentioned the additional oxygen content [13, 26] and the improved lubricity by the biodiesel content [21, 28, 29] as the causes of the higher brake thermal efficiency.

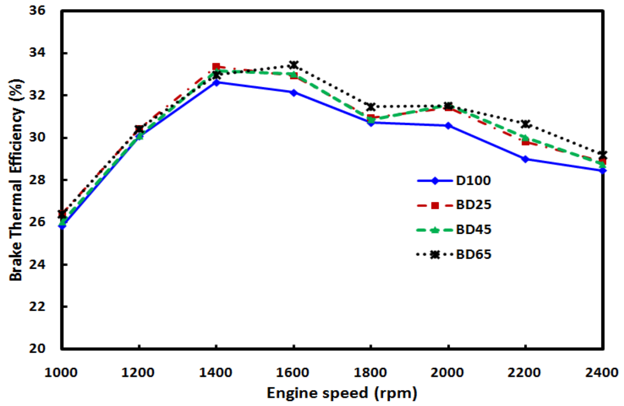


Figure 6. Brake thermal efficiency with engine speed at full-load

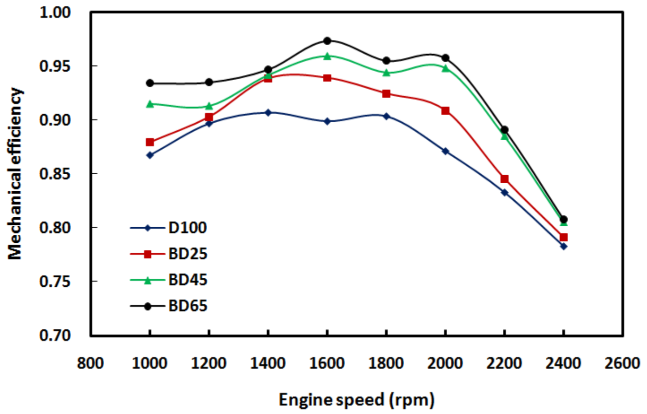


Figure 7. The mechanical efficiency with engine speed at full-load

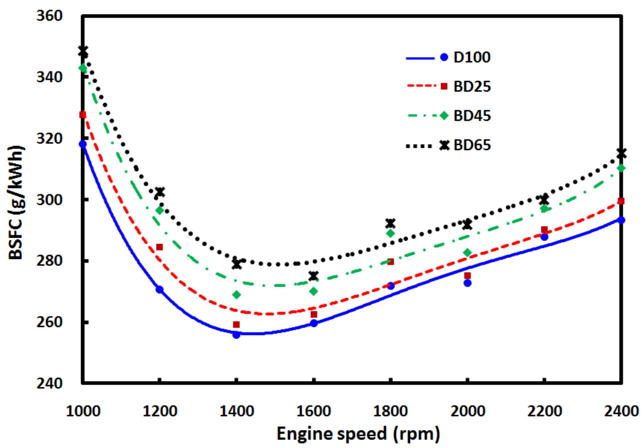


Figure 8. Brake specific fuel consumption (BSFC) with engine speed at full-load

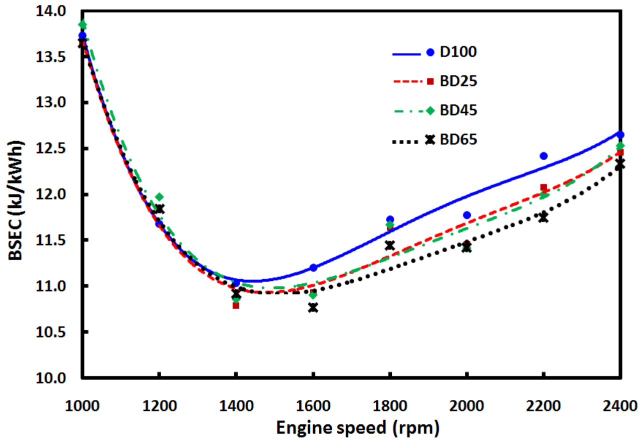


Figure 9. Brake specific energy consumption (BSEC) with engine speed at full-load

The variations in the brake specific fuel consumption (BSFC) with engine speed at full-load condition are shown in Fig. 8. It is clearly seen that the brake specific fuel consumption is higher with the increase of biodiesel content. This could be mainly caused by the lower heating value of the biodiesel-blends fuel. The higher density of the biodiesel that might affect the combustion could be the other reasons for the higher BSFC with biodiesel blends. Fuel is delivered by volume; however, the vehicles are moved by the energy of the fuel. It is important to present the brake specific energy consumption as comparison to the brake specific fuel consumption. Fig. 9 showed in spite of the diesel fuel consumed the lowest BSFC; it resulted in the highest energy to run the engine.

IV. CONCLUSIONS

The performance and emission characteristics of an IDI diesel engine fuelled with diesel and diesel-biodiesel blends were experimentally conducted. The results showed that the biodiesel content decreased the engine torque and power. The lower torque power reached in the present study might be mainly affected by the lower LHV of the biodiesel, and also the worse combustion due to higher density of the biodiesel compared to the diesel fuel. The loss of power due to lower heating value of biodiesel was not as high as the difference in their heating value. The better lubricity of biodiesel might be mentioned as reason to this power recovery. The brake thermal efficiency of the biodiesel blends fuel was higher than those of neat diesel fuel. The better lubricity of biodiesel could be also observed from the mechanical efficiency. The brake specific fuel consumption is higher with the increase of biodiesel content. This could be mainly caused by the lower heating value of the biodiesel-blends fuel. The higher density of biodiesel that might affect the combustion could be the other reasons for the higher BSFC with biodiesel blends. In spite of the diesel fuel consumed the lowest BSFC; it resulted in the highest energy to run the engine.

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