การเปรียบเทียบสมรรถนะและการปล่อยสารมลพิษต่าง ๆ ของเครื่องยนต์ดีเซลที่ใช้ B50 และเชื้อเพลิงร่วมระหว่างการอัดแก๊สชีวภาพและ B50 สำหรับเชื้อเพลิงทางเลือก

Comparative Performance and Emissions of Diesel Engine Using B50 and Dual Fuel between Compressing Producer Gas and B50 for an Alternative Fuel

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Received : 13 November 2018

Revised : 13 May 2019

Accepted : 2 July 2019

บทคัดย่อ

วัตถุประสงค์หลักของงานวิจัยนี้ เป็นการเปรียบเทียบระหว่างการใช้ดีเซลผสมกับไบโอดีเซลร้อยละ 50 (B50) และการใช้เชื้อเพลิงร่วมระหว่าง B50 และการอัดแก๊สชีวภาพระหว่างอัตรา 76 ถึง 125 lpm สำหรับเครื่องยนต์ดีเซลแบบซุปเปอร์ชาร์จซึ่งต่อกับเครื่องกำเนิดไฟฟ้า ความเร็วรอบของเครื่องยนต์ถูกปรับจาก 1,000 ถึง 1,600 rpm ไบโอดีเซลซึ่งผสมกับดีเซลเป็นปาล์มเอทิลเอสเทอร์ และแก๊สชีวภาพถูกผลิตจากถ่านไม้โดยใช้เตาแก๊สซิไฟเออร์แบบไหลลง ผลการทดสอบเครื่องยนต์เมื่อใช้ B50 เทียบกับดีเซล พบว่า สมรรถนะของเครื่องยนต์ลดลงเล็กน้อย และการปล่อยสารมลพิษต่าง ๆ ถูกลดลงอย่างมากยกเว้นคาร์บอนไดออกไซด์ ในทางตรงกันข้าม การอัดแก๊สชีวภาพเมื่อใช้ร่วมกับ B50 นำไปสู่การเพิ่มขึ้นของสมรรถนะเครื่องยนต์ แต่การปล่อยสารมลพิษต่าง ๆ ถูกเพิ่มขึ้นตามการเพิ่มแก๊สชีวภาพ อย่างไรก็ตาม การใช้เชื้อเพลิงร่วมระหว่าง B50 และแก๊สชีวภาพที่ 125 lpm มีการประหยัดเชื้อเพลิงสูงถึงร้อยละ 21.67 และ 8.78 เมื่อเทียบกับการใช้ B50 และดีเซลเพียงอย่างเดียว สำหรับการประยุกต์ใช้กับเครื่องยนต์ดีเซลนั้น การใช้ B50 ร่วมกับแก๊สชีวภาพที่ 93 lpm ดีที่สุด เนื่องจากสมรรถนะของเครื่องยนต์ใกล้เคียงกับดีเซล และการปล่อยสารมลพิษต่าง ๆ เพิ่มขึ้นเล็กน้อย

คำสำคัญ : B50, แก๊สชีวภาพ, เครื่องยนต์ดีเซล, สมรรถนะ, สารมลพิษต่างๆ

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Abstract

The main objective of this research is the comparison between the use of diesel blended to 50% biodiesel (B50) and dual fuel between B50 and compressing producer gas from 76 to 125 lpm for a supercharging diesel engine connected with a generator. The engine speed was adjusted from 1,000 to 1,600 rpm. Biodiesel, which was mixed with diesel, was the palm ethyl ester, and producer gas was produced from the charcoal by using a downdraft gasifier. Results of engine test using the B50 compared with diesel indicate that the engine performance decreased slightly and the emissions were decreased galore, except carbon dioxide. On the other hand, supercharging producer gas combined with B50 leads to an increase in engine performance, but various pollutants were increased with increasing producer gas. However, the use of dual fuel between B50 and producer gas at 125 lpm had high fuel saving to 21.67% and 8.78% as compared with using B50 and diesel only. For applying to the diesel engine, the use of B50 combined to producer gas at 93 lpm is the best because the engine performance was similar to diesel and emissions were increased slightly.

Keywords : B50, producer gas, diesel engine, performance, emissions

Introduction

Due to the depletion of crude sources, uncertainty in petroleum prices, and innumerable pollutants have led to the use of renewable fuels, especially biodiesel and biomass (Hemanth *et al*., 2017). Biodiesel is being applied with diesel engines because of an alternative fuel synthesized from plant oils and alcohols through transesterification reaction using acid or alkali (Santasnachok *et al*., 2018). Engine testing results using biodiesels produced from some plant oils such as palm, sunflower, rapeseed, and jatropha, compared with diesel shown that the engine performance was decreased slightly, but the pollutants were decreased remarkably, particularly hydrocarbon (HC), carbon monoxide (CO), and black smoke. However, the use of pure biodiesels led to damage to the parts of the fuel injection system because of the high fuel viscosity (Shahir *et al*., 2015; Basha *et al*., 2009).

In the simple basis, the best way is the use of diesel and biodiesel blend because of reducing fuel viscosity, increasing fuel heating value, and decreasing production costs (Basha *et al*., 2009). In Thailand, biodiesel is nowadays being mixed with diesel at a ratio of 5 to 7% (B5 to B7) replacing to the use of diesel as increased to 10% in the future (Santasnachok *et al*., 2018; Sutheerasak & Chinwanitcharoen, 2018). Other countries, particularly India and Malaysia, are focusing the use of diesel blended to 50%biodiesel (B50) for the diesel engines because of a little change of some properties, especially fuel viscosity and heating value, led to decrease of the engine performance slightly. B50 did not damage the fuel injection system of these engines, as well as the various emissions (such as CO, HC, and, black smoke), were significantly reduced (Nayak & Mishra, 2017; Mahgoub *et al*., 2016).

Biomass is another renewable energy pushed into the widespread usage in the various countries. It can be converted to producer gas by using the biomass gasification process, but the auto-ignition temperature was typically above 500°C which could not ignite within the diesel engines (Sutheerasak *et al*., 2018). Dual fuel mode is a possible technique to apply this gas with the diesel engines because of non-modified engines and low cost. Primary fuel is injected into the engine cylinder, while syngas is secondary fuel mixed to air within the mixing box or carburetor before sent into an intake manifold (Sutheerasak *et al*., 2018; Mattson *et al*., 2016; Das *et al*., 2012).

Many studies from the engine performance test using various oils and producer gas or syngas in the dual fuel mode have been carried out. Some researchers (Sutheerasak *et al*., 2018; Das *et al*., 2012) investigated the dual fuel mode from using diesel and supercharging syngas, while other researchers (Singh & Mohapatra, 2018; Lal & Mohapatra, 2017) increased the syngas quantity combined to diesel by changing the compression ratio. As a result, the engine performance was changed, fuel saving was improved, and engine emissions, particularly CO, HC, and black smoke, were increased. Several researchers (Hemanth *et al*., 2017; Nayak & Mishra, 2017; Mahgoub *et al*., 2016; Mattson *et al*., 2016; Yaliwal *et al*., 2016) generated producer gas from various biomasses, such as jatropha seeds, calophyllum inophyllum, coconut shell, etc., to combine with the diesel mixed to biodiesel in ratio of 10 to 50%vol and pure biodiesel on dual fuel. Results demonstrated that specific energy consumption (SEC) and level of engine pollutions, such as CO, HC, and black smoke, were decreased but carbon dioxide (CO_2) and fuel saving did not decrease to compare with these oils and diesel. However, the use of pure biodiesel had lower engine performance than using diesel mixed to biodiesel in the ratio of 10-50% combined to syngas on dual fuel mode (Yaliwal *et al*., 2016; Nayak & Mishra, 2017).

Moreover, previous literature reviews mainly focused on dual fuel between producer gas and biodiesels in term of methyl esters produced from plant oils in those countries and methanol, which was expensive. On the other hand, the study of producer gas combined to diesel mixed to 50%biodiesel (ethyl ester) synthesized from ethanol has a little. Furthermore, previous researches aimed at the constant gas flow rate as compressing producer gas was mostly combined with diesel on dual fuel (Sutheerasak *et al*., 2018; Das *et al*., 2012). The objective of proposed work is to compare the use of only B50 with dual fuel between B50 and supercharging producer gas, which was produced from charcoal biomass, to increase the gas flow rate from 76 to 125 lpm on performance and emissions of a diesel engine which used the twin-blower supercharger at various speeds and full load.

Methods

Producer gas as a potential fuel

Producer gas was generated from a downdraft gasifier by using charcoal biomass produced from timber wood, which was commonly used charcoal, and the amount of air was controlled by a blower. Specifications of the gasifier are shown in Figure 1 and Table 1. First, charcoal about 10-15 kg from a weighing scale was fed into this gasifier through the top. Air was entranced at the side of this gasifier using a blower to accelerate the reaction time of the gasification process, which was investigated from temperatures of the combustion zone and hot producer gas by utilizing the temperature meter. Next, this gas was sent into a cyclone to trap the solid particles, and the flame ability from a flare was investigated before it was entered to a wet scrubber, which decreased its temperature and removed tar by using the water spray from the top side impinged with the gas.

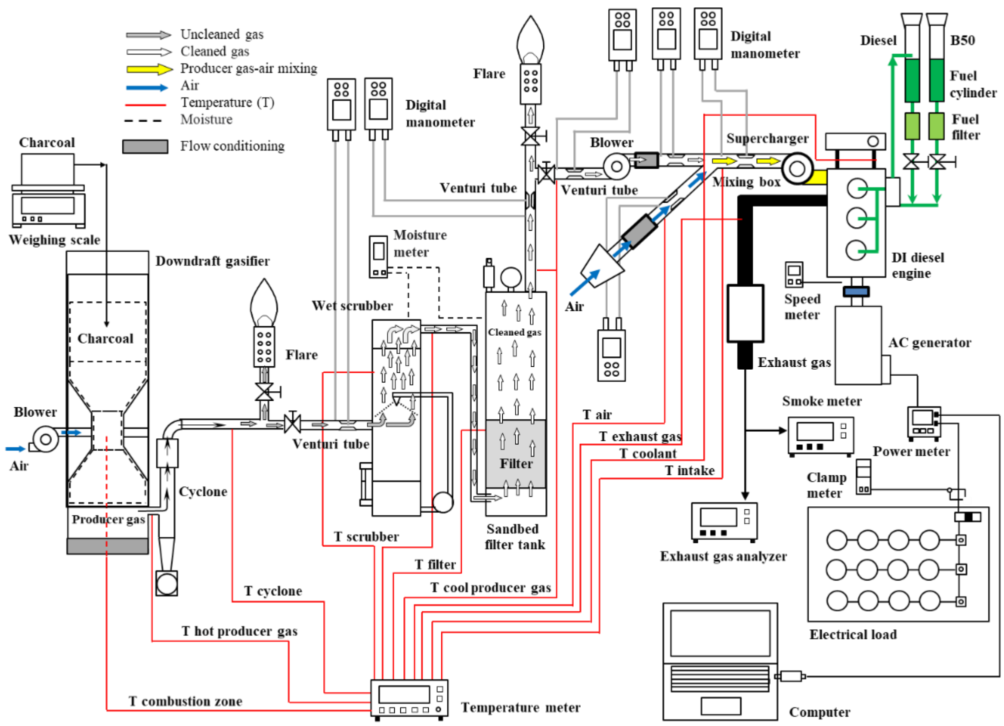


Figure 1 Schematic of the experimental setup

Table 1 Gasifier specification

Item	Description
Type of gasifier	Downdraft gasifier
Maximum capacity (kW_{th})	75
Rate charcoal biomass consumption (kg/h)	5 to 6
Maximum rate gas flow (m^3/h)	96 (Charcoal)
Calorific value (MJ/kg)	29.60
Biomass size (mm)	10 to 30
Efficiency (%)	70 to 75
Equivalence ratio	0.12 to 0.16

However, the cooled gas efflux from the wet scrubber had the humidity in various quantities. To clean and reduce the moistness, the producer gas was, then, sent to a sandbed filter tank consists of sawdust, coarse sand, and fine sand respectively as studied from (Pathak *et al*., 2007). Again, there was the investigation of gas components from the sandbed filter by gas chromatography to analyze the chemical compositions of syngas and calorific value, as shown in Table 2. Result of producer gas compositions in this experiment indicates that there was a lesser amount of water vapor because of cleaning syngas in the wet scrubber; therefore the calorific-value calculation was studied from (Kirsanovs & Žandeckis, 2015; Bhattacharya *et al*., 2001).

Table 2 Chemical compositions of producer gas and calorific value

Properties	Volume percentage
Hydrogen (%)	7.5±2.5
Carbon monoxide (%)	29.5±1.5
Carbon dioxide (%)	1.5±0.5
Methane (%)	1.5±0.5
Nitrogen (%)	57.5±2.5
Water vapor (%)	2.5±0.5
Calorific value (MJ/m^3)	5.08±0.48

Finally, this gas was compressed into the engine by using the twin-blower supercharging system. Single blower compressed this gas into a Y-shape mixing box, and it was absorbed by the second blower to send this gas into the combustion chamber. For measuring the flow rate of this gas and air, the flow conditioning was installed before the Y-shape mixing box, and a venturi tube and a digital manometer were applied in this research.

Preparation of diesel mixed with 50% biodiesel

Diesel mixed with 50% biodiesel (B50) was produced from the fuel ratio of diesel and biodiesel was 50:50 %vol as studied from (Sutheerasak & Chinwanitcharoen, 2018). The reactants of such biodiesel were palm ethyl ester synthesized by transesterification process using oleic palm oil and ethanol using sodium hydroxide as discussed in (Santasnachok *et al*., 2018). The properties of B50 and diesel under various ASTM procedures were shown in Table 3 indicating that the pour point increased to 10.2 °C, the cloud point increased to 3 °C, the flash point increased to 65.2 °C, the fuel density increased to 3.41%, the kinematic viscosity increased to 51.38%, and the lower heating value (LHV) decreased to 7.80% respectively. However, B50 used in this study is compared with the PME50 from (Abdul Aziz *et al*., 2006), which produced from 50% diesel and 50% palm methyl ester (PME) by volume. It was indicated that the pour point decreased to 3.2 °C, the cloud point decreased to 5 °C, the flash point increased to 0.2 °C, the fuel density decreased to 3.19%, the kinematic viscosity decreased to 4.36%, and the LHV decreased to 3.52% respectively.

Table 3 Fuel properties

Items	Pour point (°C)	Cloud point (°C)	Flash point (°C)	Density (kg/m^3)	Viscosity (mm^2/sec)	LHV (MJ/kg)
ASTM	D97	D2500	D93	D1298	D445	D240
CSD	-	Min -6	Min 75	816-840	2.5-5.7	-
Diesel	-8.0	7.0	45.0	821	2.90	44.36
B50	2.2	10.0	110.2	849	4.39	40.90

Therefore, properties of B50 using in this research is slightly lower than the results of (Abdul Aziz *et al*., 2006), except for the flash point and LHV. For applying in the future, B50 used in this research was compared the common standard diesel (CSD) as indicated in the results of (Ghazanfari *et al*., 2017) shown that this oil had the fuel viscosity in range of 2.5 to 5.7 mm^2/s because this range demonstrated to applying with the fuel injection system of diesel engines. Therefore, B50 produced in this research had the kinematic viscosity within the prescribed range and could be utilized as an alternative fuel with the diesel engines.

Experimental setup of the engine testing

The experiments were carried out on a four-stroke three-cylinder direct injection diesel engine [Model, John Deere 3029DF150; low speed diesel engine; capacity 2.9 L; power (max.) 43 kW @ 2,500 rpm; compression ratio 17.2.1], while this engine had increased the twin-blower supercharger to compress the producer gas into an intake manifold of this engine. For measuring the output power, a generator 20 kW_e was applied in this experiment, as directly coupled to this engine by using electric lamps to increase the electrical load (Figure 1). Recording data of output electrical power to depend on the electrical load was analyzed from a power meter of richtmass RP-96EN through the clamp IMARI-CT100/1A by converting the signal into the richtmass RS485 with USB data converter and hardlock for RP series to connect with a computer. In addition, there was the calibration of power-meter parameters of richtmass RP-96EN by comparing with a clamp meter. For investigating the engine speed and the flow rate of diesel and B50 to calculate the fuel consumption rate, this research used a speed meter and a fuel cylinder. In case of recording temperatures, such as coolant, intake, exhaust gas and gasifier system, they were measured by using K-type thermocouple to connect with temperature meters. For analyzing concentration of exhaust gas emissions, such as CO_2, CO and HC, they were measured from MOTORSCAN: 8020 eurogas emission analyzer by using IR Bench (Infrared measuring) method. In measuring the black smoke levels indicated in term of smoke opacity, MOTORSCAN: 9010 opacity meter/smoke detector was applied in this experiment.

Experimental procedure

First of all, the engine was warmed up about 15-20 minutes when the room temperature was determined at 33±2 ^{o}C. After engine operation was stable, experiments were started up by using diesel and B50. The engine speed was adjusted from 1,000 to 1,600 rpm by measurement error was set at ±50 rpm. Engine load was controlled at the equally full load by electrical power was determined from 8.6 to 20.0 kW_e. Fuel volume was fixed at 20 ml to calculate the mass and volume flow rate of oils (diesel and B50). Final, parameters, such as air-fuel flow rate, engine speed, electrical power, temperatures, and emissions, were recorded to compare the engine performance from using B50 with diesel. Next, the dual fuel mode between B50 and producer gas (PG) would be used. Producer gas from gasifier system was sent by the single blower at 76 lpm and sent to blend with air in the mixing box. The mixture was, then, sent into the intake manifold and the combustion chamber by the second blower, which was connected with this engine, where the B50 was separately injected at the normal timing. Again, the engine performance test conditions, as well as the recorded parameters, would be the same as those for both diesel and B50 oils only. They were the flow rates of diesel, B50, producer gas, and air, the electrical power, the temperatures, the exhaust gas emissions, etc. After finish using the producer gas on duel fuel at a flow rate of 76 lpm, others flow rates of the producer gas would, then, be introduced and the same conditions and parameters would be recorded. All the producer gas flow rates used in this study were 76, 79, 85, 93, 103, 116, and 125 lpm, and terms of B50 combined with producer gas (B50+PG) from 76 to 125 lpm were demonstrated as B50+PG76, B50+PG79, B50+PG85, B50+PG93, B50+PG103, B50+PG116, and B50+PG125lpm.

All period of the engine tests were between 50 to 100 hours, and all parameters were repeated at least 3 times in each condition as studied from (Sutheerasak *et al*., 2018; Martyr & Plint, 2007). Engine test results were shown in term of the electric thermal efficiency, the specific energy consumption (SEC), fuel consumption rate (FCR), the exhaust gas temperature (EGT), and the emissions depended on the mean effective pressure (MEP) as studied from (Sutheerasak *et al*., 2018; Deshmukh *et al*., 2008). MEP was calculated from the multiplication of electrical power at engine speed from 1,000, 1,200, 1,400, and 1,600 rpm and the number of revolutions per power stroke divided by the multiplication of displacement volume and these speeds. Maximum electrical power in each speed was shown at 8.81±0.005, 12.67±0.018, 15.85±0.004 and 20.28±0.005 kW_e respectively, while measurement error was controlled between ±0.005 and ±0.018 kW_e. As a result, MEP was increased at 10.73±0.017, 12.52±0.013, 13.99±0.027 and 15.61±0.089 bar respectively.

Results

All result of the engine-performance test illustrates that the electric thermal efficiency (ETE), ratio of electrical power and total input energy, is changed with increasing syngas and MEP, as shown in Figure 2 on the left side. The best efficiency occurred at 13.99 bar of MEP by using the speed 1,400 rpm because there was the maximum efficiency as explained in (Martyr & Plint, 2007). In addition, this MEP gave the lowest SEC. Therefore, the study of performance and emissions engine from using diesel, B50, and B50+PG from 76 to 125 lpm is considered under this MEP. Using B50 compared with diesel in this MEP, the ETE decreased to 2.26% whereas the ETE from using the B50+PG from 76 to 125 lpm increased from 0.55 to 4.53% as compared with the use of B50 only. This research shows that the use of B50+PG at 125 lpm (B50+PG125 lpm) has higher ETE than using B50 only, and the ETE from using B50+PG125 lpm increased to 2.28% as compared with using diesel only. Moreover, this research found that using B50+PG at 93 lpm (B50+PG93 lpm) gave the ETE similar to diesel. The measurement deviation of the ETE was at ±6.06%.

Similarly, the SEC is depended with increasing producer gas and MEP, as demonstrated in Figure 2 on the right side. Minimum SEC occurred at 13.99 bar of MEP, while the SEC from using B50 increased to 8.90% as compared with diesel. For using B50+PG from 76 to 125 lpm, the SEC decreased from 13.90 to 12.05 $MJ/kW_e.hr$. As a result, energy saving was increased from 2.12 to 15.17% as compared with using B50, respectively. Moreover, comparing B50+PG125 lpm with diesel shows that the SEC decreased to 13.88%, and the use of B50+PG93 lpm gave the SEC similar to diesel. The measurement deviation of SEC was at ±5.82%.

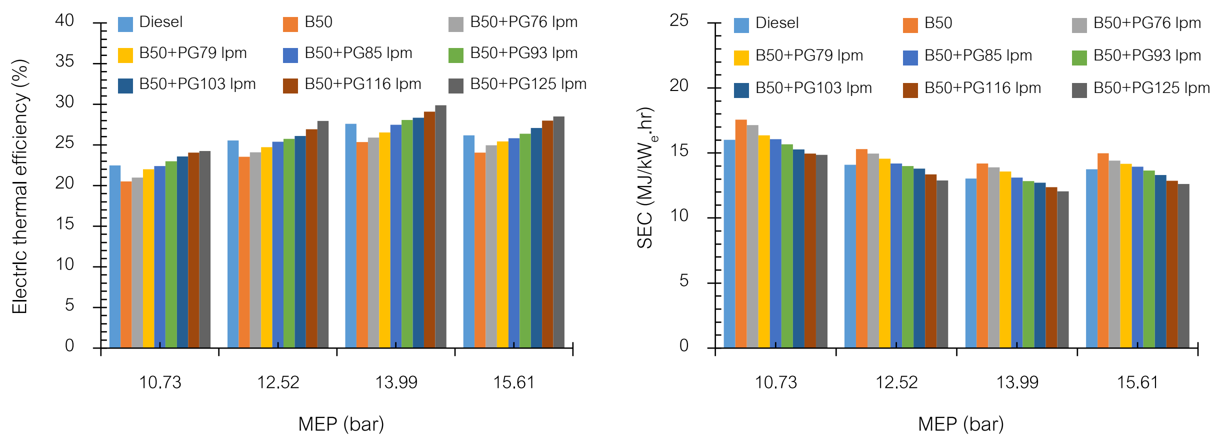


Figure 2 Electric thermal efficiency and SEC with various MEP

Figure 3 on the left side shows that the FCR, the fuel volume per unit of time, increases with increasing MEP, and it is decreased with increasing gas flow rate. Comparing the use of B50 with diesel at 13.99 bar of MEP indicates that the FCR was increased to 16.45%. On the other hand, the FCR using B50+PG from 76 to 125 lpm was decreased from 6.62 to 5.18 lph. As a result, the fuel saving was added from 5.96 to 21.67% as compared with B50, respectively. Use of B50+PG125 lpm enlarged the fuel saving to 8.78% as compared with diesel, whereas using B50+PG93 lpm had the fuel-saving similar to diesel. The measurement error of FCR was at ±5.28%. Again, this figure on the right side indicates that the trends of EGT increase with increasing producer gas and MEP. Use of B50 had increased the EGT to 19 ^{o}C as compared with diesel. Moreover, the use of B50+PG from 76 to 125 lpm had raised the level of EGT as increased from 24 to 84 ^{o}C comparing with using B50 only. As compared with using diesel only, the EGT of B50+PG125 lpm was increased to 103 ^{o}C, and the EGT from using B50+PG93 lpm was increased to 83 ^{o}C. The measurement deviation of EGT was at ±0.3 ^{o}C.

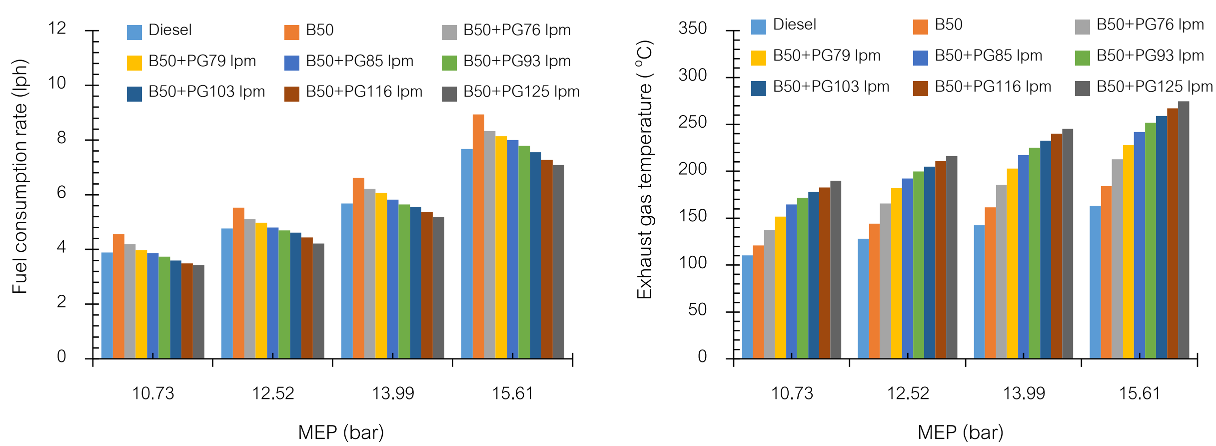
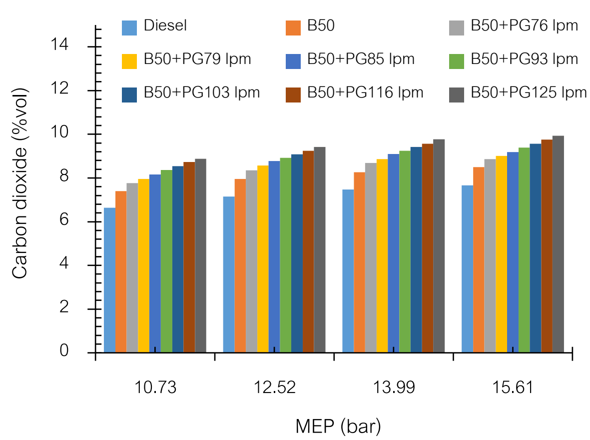


Figure 3 Fuel consumption rate and exhaust gas temperature with various MEP

The releases of carbon dioxide (CO_2) increase with increasing producer gas and MEP is shown on the left side of Figure 4. At 13.99 bar of MEP, the CO_2 release from using B50 increased to 0.79 %vol as compared with diesel and the use of B50+PG from 76 to 125 lpm added the levels of CO_2 from 0.43 to 1.50 %vol as compared with B50. Moreover, using B50+PG125 lpm demonstrates that the CO_2 release was added to 2.30 %vol, whereas using B50+PG93 lpm released the CO_2 at 1.77 %vol as compared with diesel. Figure 4 on the right side shows the release of carbon monoxide (CO). It is decreased with increasing MEP and increased with increasing gas flow rate. Use of B50 reduced the CO emission to 0.07 %vol as compared with diesel at 13.99 bar of MEP. Whereas the use of B50+PG from 76 to 125 lpm leads to the increase of CO levels, they were enlarged from 0.12 to 0.38 %vol as compared with B50. Moreover, the use of B50+PG125 lpm added the CO emission to 0.31 %vol but using B50+PG93 lpm released the CO at 0.17 %vol as compared with diesel respectively. The error of measuring CO_2 and CO emissions was at ±0.28 and ±0.25 %vol, respectively.

Figure 5 on the left side indicates the levels of HC increased with increasing producer gas and MEP. At 13.99 bar of MEP, the HC emission from using B50 decreased to 4.94 ppm as compared with diesel, but the use of B50+PG from 76 to 125 lpm increased the HC releases from 7.00 to 27.67 ppm as compared with B50. Furthermore, the use of B50+PG125 lpm added the HC level to 22.73 ppm, but the using B50+PG93 lpm released the HC at 11.06 ppm as compared with diesel, respectively. While the error of measuring HC emissions was at ±0.75 ppm.



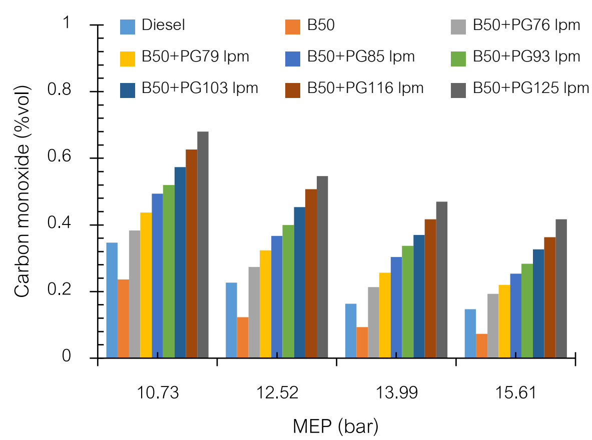


Figure 4 Carbon dioxide and Carbon monoxide levels at various MEP

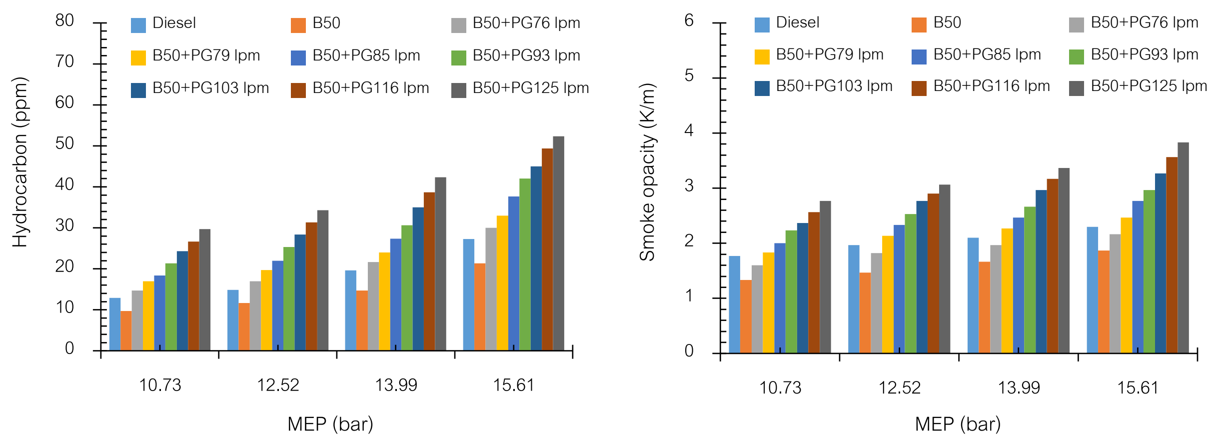


Figure 5 Hydrocarbon and Smoke opacity levels at various MEP

For investigating the levels of black smoke to confirm the results of CO and HC emissions, the black-smoke releases are indicated in term of the smoke opacity shown in Figure 5 on the right side. Smoke opacity levels increase with increasing producer gas and MEP. Smoke opacity from using B50 decreased to 0.43 K/m led to level of black smoke decreased to 20.65% as compared with diesel at 13.99 bar of MEP. On the other hand, the use of B50+PG from 76 to 125 lpm increased the smoke opacity levels from 0.30 to 1.70 K/m led to the release of black smoke increased very galore as compared with B50. Whereas the use of B50+PG125 lpm is higher smoke opacity than diesel, it was increased to 1.27 K/m and the level of black smoke was increased to 60.32% as compared with diesel. For using B50+PG93 lpm compared with diesel, the smoke opacity increased at 0.57 K/m and black smoke level increased at 26.98%. The measurement error of smoke opacity level was at ±0.19 K/m.

Discussion

Comparative results of performance and emissions were conducted on diesel engine using the B50 and the dual fuel between B50+PG from 76 to 125 lpm. Results were described below.

Electric thermal efficiency

First result of engine performance test from using B50 compared with diesel shows that the use of B50 gives lower ETE than diesel (Figure 2 on the left side) because of lower fuel heating value (Table 3) led to the increase of fuel consumption as tested at equally electrical power (Sutheerasak & Chinwanitcharoen, 2018; Santasnachok *et al.,* 2018). As compared with results of (Abdul Aziz *et al.,* 2006), using B50 gives higher efficiency because of high O_2 content from B50 led to more complete combustion (Basha *et al.,* 2009). For using B50+PG from 76 to 125 lpm, they have improved ETE, and they have more ETE than using B50 and diesel only. Compressing producer gas at 125 lpm combined with B50 is the best, and it reduces the limitations of using B50. Moreover, using B50 and supercharging producer gas at 93 lpm in dual fuel mode gives the ETE similar to diesel. As compared with results of (Nayak & Mishra, 2017), results of this research have higher efficiency, and they are consistent with results of (Sutheerasak *et al*., 2018; Das *et al*., 2012). Because using B50+PG was faster ignition timing than the use of both oils only, the increase of more gas quantity as combined with B50 led to start of combustion very quickly. As a result, there was a reduction of injected B50, and the input energy from using B50 was replaced by highly gas-quantity energy. Therefore, the total input energy from using B50+PG was decreased because the calorific value of producer gas was lower than B50. While the electrical power was used equally, but the total input energy of B50+PG was reduced. Therefore, the ETE had to be increased due to electric thermal efficiency equaled the ratio of electrical power and total input energy.

Specific energy consumption

Result of SEC in Figure 2 on the right side shows that the use of B50 has increased the SEC as compared with diesel because of the limitations of B50 properties, which was higher fuel density and lower heating value than diesel, which led to the increase of fuel consumption as tested at equal load (Sutheerasak & Chinwanitcharoen, 2018). On the other hand, using B50+PG leads to a decrease of SEC and the increase of energy saving as compared with using B50 and diesel only. Moreover, the use of B50+PG125 lpm reduces the most SEC and the use of B50+PG93 lpm gives the SEC similar to diesel. As compared with results of (Nayak & Mishra, 2017), results of this research have lower SEC and higher energy saving because (Nayak & Mishra, 2017) used the constant syngas led to a slight decrease of the SEC. However, they are similar to (Sutheerasak *et al*., 2018; Das *et al*., 2012). Because this research increases the gas flow rate by using twin-blower supercharger led to start of combustion quickly. As a result, injecting B50 was decreased since more producer gas quantity replaced with B50 led to the decrease in energy consumption from using B50. In addition, the SEC was the opposite of electrical efficiency. The increase in electrical efficiency led to a reduction of the SEC.

Fuel consumption rate

Use of B50 gives higher FCR than diesel that led to consuming more fuel than diesel explained by (Sutheerasak & Chinwanitcharoen, 2018) as indicated in Figure 3 on the left side. Because B50 had lower calorific value than diesel, fuel consumption from using B50 was increased as tested at equally electrical power. For using B50+PG compared with the use of B50 and diesel, the FCR decreases with increasing producer gas quantity. Use of B50+PG93 lpm gives the FCR similar to diesel. Moreover, the use of B50+PG125 lpm increases the fuel-saving more than the use of both oils (as increased to 21.67%), and B50 with diesel (as increased to 8.78%). Such an increase due to high producer gas quantity replaced more B50 and led to less fuel injection and more fuel saving than using both oils (Sutheerasak *et al*., 2018; Das *et al*., 2012), as compared with (Nayak & Mishra, 2017; Hemanth *et al*., 2017), increasing producer gas up to 125 lpm combined to B50 gives more fuel saving than the results of both researches because of more replacement of B50.

Exhaust gas temperature

For investigating the level of EGT from using B50 compared with diesel, B50 has higher EGT than diesel as demonstrated in Figure 3 on the right side and consistent with the result of (Sutheerasak & Chinwanitcharoen, 2018). Since the concentration of O_2 within B50 led to highly burning rate between B50 and O_2 content from the air quantity and then there was the complete combustion resulting in higher burning temperature in the premixed combustion phase than diesel. Moreover, using B50 and supercharging producer gas on dual fuel has the levels of EGT to enlarge with increasing syngas and higher than the use of B50 and diesel. Such increase is consistent with (Nayak & Mishra, 2017; Sutheerasak *et al*., 2018) explained from the producer gas properties which had the CO_2 and CO contents (Table 2) as combined to B50 reacting with O_2 content from the amount of air. It changed the combustion phenomena in the diffusion combustion phase, which led to an increase of burning temperature in this stage. Moreover, compressing producer gas had reduced the air quantity before sent to the combustion chamber led to the fuel-rich mixture combustion. As a result, the CO_2 and CO contents within producer gas were burned with the less O_2 content caused to the increase of late combustion period until the exhaust valve was opened.

Carbon dioxide release

Use of B50 compared to diesel indicating that the release of CO_2 is increased, as shown in Figure 4 on the left side it is consistent with the increase of EGT and result of (Sutheerasak & Chinwanitcharoen, 2018). The use of B50 gives higher CO_2 release than (Abdul Aziz *et al*., 2006) because the O_2 element within B50 was higher and led to complete combustion within the phases of diesel-engine combustion (Basha *et al*., 2009). The number of carbon molecules from this oil was reacted with more O_2 from the composition of B50 and air led to the increase of CO_2 release. Moreover, supercharging producer gas combined with B50 accelerated the increase of CO_2 release. As compared with B50 and diesel, they release the CO_2 lower than dual fuel mode. This result is similar to the outcome of (Nayak & Mishra, 2017; Sutheerasak *et al*., 2018) because the generated producer gas consisted of both CO and CO_2 quantities (Table 2). While increasing producer gas combined to this oil reacted with O_2 content within the air which was limited by compressing producer gas, innumerable carbon content was burned with O_2 content and unburned gas, which had the CO_2 content, was released after burning reaction between more producer gas with O_2 content from the air element. As a result, there was a steep rise in the release of CO_2 (Garcia-Armingol & Ballester, 2015; Whitty *et al*., 2008).

Carbon monoxide emission

The demonstration of the use of B50 reduces the CO emission as compared with diesel is shown in Figure 4 on the right side; this is consistent with (Sutheerasak & Chinwanitcharoen, 2018), while the use of B50 gives lower CO emission than the result of (Abdul Aziz *et al*., 2006). Because the formation of CO depended on the amount of O_2 required for the combustion reaction, B50 had the O_2 element enhanced the combustion reacting with C molecules led to more release of CO_2 led to the decrease of CO emission. On the other hand, the compressing producer gas combined with B50 increases more CO emission than using B50 and diesel. This is similar to the result of (Nayak & Mishra, 2017; Hemanth *et al*., 2017; Sutheerasak *et al*., 2018) because of the compressing producer gas decreasing the amount of air sent to the diesel engine as well as the amount of O_2 required for complete combustion decreased with increasing gas flow rate and the chemical compositions of producer gas consisted of both CO and CO_2 quantities (Table 2). Both reasons led to the combustion of high fuel-rich mixture caused to high incomplete combustion in the diffusion combustion phase. As a result, the formation of CO emission is very highly (Garcia-Armingol & Ballester, 2015; Whitty *et al*., 2008).

Hydrocarbon emission

The HC emission from using B50 is lower than diesel as shown in Figure 5 on the left side, and this result is consistent with (Sutheerasak & Chinwanitcharoen, 2018) since the concentration of O_2 within B50 which improved the combustion reaction between B50 and O_2 content from the air led to complete combustion than diesel. On the other hand, the release of HC from compressing producer gas combined to B50 is higher than using B50 and diesel; and this result is similar to the conclusion of (Nayak & Mishra, 2017; Sutheerasak *et al*., 2018). The cause of increasing HC emission is explained from the direct result of incomplete combustion from the high fuel-rich mixture because the producer gas contains the large number of C and H molecules which came from CO_2, CO, and CH_4. The more producer gas content combining to B50 injection will result in the less amount of O_2. Therefore, the more insufficient amount of O_2 will increase the CO and HC emission. Next, the chemical reaction of combustion between dual fuel and O_2 content, which was decreased as increasing gas flow rate, releases the high CO_2 emission, and some H molecules are reacted with little O_2 molecules to produce the water (H_2O). At the same time, there is not enough O_2 molecule to react with too many molecules of the C and H that leads to the formation of unburned hydrocarbon at unburned zone. As a result, there is the formation of undesirable combustion products, especially the HC, CO, and black smoke (Garcia-Armingol & Ballester, 2015; Whitty *et al*., 2008).

Black smoke level

The release of black smoke is described by the level of smoke opacity. Figure 5 on the right side indicates that the use of B50 has lower smoke opacity than diesel, while this is similar to (Sutheerasak & Chinwanitcharoen, 2018) because of the O_2 element within B50 enhanced the burning rate during the diffusion combustion which subsequently reduced the smoke density. On the other hand, the use of B50 and compressing producer gas on dual fuel led to higher black smoke level than using B50 and diesel. Results of this research have higher smoke opacity than the results of (Nayak & Mishra, 2017) because this research used more producer gas quantity. However, these results are similar to (Sutheerasak *et al*., 2018) since increasingly incomplete combustion as result of an over-rich combustion mixture with increasing gas flow rate. The amount of C molecules increase from the increasing producer gas content while the amount of O_2 molecules decrease due to reducing the air entrance. Moreover, the increase of smoke opacity was confirmed from a higher level of CO and HC emissions (Garcia-Armingol & Ballester, 2015; Whitty *et al.*, 2008).

Conclusions

Results of performance and emission characteristics of diesel engine using the B50 and the dual fuel between supercharging producer gas and B50 are summarized as follows.

Use of B50 gives the engine performance to decrease slightly. For example, the ETE decreased to 2.26% and the SEC increased to 8.90% as compared with diesel because of lower heating value and higher fuel density led to fuel consumption. On the other hand, the exhaust gas emissions, especially CO, HC, and black smoke, are significantly reduced because of the more O_2 content within B50 led to more complete combustion. In addition, the B50 had slightly higher fuel viscosity than diesel, but it was within the prescribed range. From these reasons, the B50 could be applied as an alternative fuel with the diesel engines in the future.

Using B50 and producer gas flow rate increased until 125 lpm in dual fuel mode show that the engine performance was higher than using B50 and diesel. Electric thermal efficiency increased to 4.53% and 2.28%, the energy saving decreased to 15.17% and 7.61%, and the fuel saving increased to 21.67% and 8.78% compared with B50 and diesel respectively. However, the CO_2 level was increased with increasing producer gas as consistent with the increase of exhaust gas temperature. In addition, the air flow rate was dropped very much as increasing producer gas up to 125 lpm and the formation of pollutions, such as CO, HC, and black smoke, are released very galore because of the high incomplete combustion. While this research found that using B50+PG93 lpm gives the engine performance similar to diesel and it had lower exhaust gas emissions than using B50+PG125 lpm Therefore, compressing producer gas should not exceed 93 lpm as combined to B50 on dual fuel.

Acknowledgements

The authors acknowledge the financial support from the Faculty of Engineering, Burapha University, Thailand. In addition, the authors thank Mr. Apisak Jiw, Mr. Kittiwat Nukul, and Mr. Wittaya Boonmak to help collect data until this research is completed well.

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