Performance and Emissions of a Turbocharging Diesel Engine Using B10 and Supercharging Syngas on Dual Fuel

Ekkachai Sutheerasak[1]*, Wirogana Ruengphrathuengsuka[2] and Surachai Sanitjai[3]

[1]Department of Mechanical Engineering, Faculty of Engineering, Burapha University, Chonburi, 20131, Thailand

[2]Department of Chemical Engineering, Faculty of Engineering, Burapha University, Chonburi, 20131, Thailand

[3]Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand

* Corresponding author. E-mail address: ekkachai@eng.buu.ac.th

Received: 10 October 2018; Accepted: 4 March 2019

Abstract

In Thailand, the ministry of energy needs to increase the use of renewable energies, especially biodiesel and syngas, more than 25%. However, blending biodiesel more than 10% provided lower engine performance significantly. Therefore, this research aims to present about the investigating performance and emissions of a turbocharging diesel engine using the diesel blended to 10% biodiesel (B10) compared with the use of B10 and syngas on dual fuel. Syngas was generated from a downdraft gasifier by using the charcoal, and it was increased the gas flow rate from 76 to 125 lpm by using a supercharger. Results of using B10 compared with diesel show that the fuel properties of B10 were similar to diesel. Engine performance was decreased slightly, but emissions, such as carbon monoxide, hydrocarbon, and black smoke, were also reduced. Results of engine test using the dual fuel between B10 and increasing syngas quantity (B10+SG) indicate that the use of B10+SG at 85 lpm had similar engine performance to using diesel only. Use of B10+SG at 125 lpm was the best because of higher engine performance and more fuel saving as compared with using B10 and diesel only. On the other hand, the use of B10+SG compared with using both oils only show that various emissions were enormously increased while the syngas quantity was increased to 125 lpm.

Keywords: B10, syngas, diesel engine, performance, emissions

Introduction

Department of Alternative Energy Development and Efficiency (DEDE) in Thailand has the policy to promote the use of biodiesel to reduce the air pollution and to use agricultural produce in this country. Therefore, the use of diesel mixed with biodiesel in the ratio of 5 to 7% (B5 to B7) is replacing to diesel nowadays (Santasnachok, Sutheerasak, Ruengphrathuengsuka, & Chinwanitcharoen, 2018). In the future, first policy of Ministry of Energy will apply the mixture of 10% biodiesel whereas researchers (Sutheerasak & Chinwanitcharoen, 2018; Vieira da Silva, Ferreira, Marques, Murta, & Vasconcelos de Freitas, 2017; Venkateswara, 2016) concluded that the use of diesel mixed with 10% biodiesel (B10) could decrease the exhaust gas emissions, such as carbon monoxide (CO) hydrocarbon (HC) and black smoke. However, engine performance from using B10 was decreased slightly to compare with diesel.

Next policy of this ministry needs to increase the use of syngas fuel, generated from various biomasses by using several gasifier types, for the internal combustion engines. Diesel engines are widely applied with the generators to produce the power generation, farm animals and subsistence farmers. However, this gas was high self-ignition temperature (typically above 500° C), and it could not be ignited in this engine (Sutheerasak, Pirompugd, & Sanitjai, 2018). Yaliwal, Banapurmath, Revenakar, and Tewari (2016) studied the use of syngas for a diesel engine by dual fuel method, where diesel was injected in normal timing and syngas was sent through the intake manifold by the use of box mixing. Because this method was non-complex, it did not destroy the various parts within this engine. Das, Dash, and Ghosal (2012) and Sutheerasak et al. (2018) investigated the use of diesel combined to increasing syngas flow rate by supercharging shown that the thermal efficiency and fuel saving was improved, but engine emissions, such as CO, HC, and black smoke, were also increased. To decrease the various pollutants from this engine, other researchers studied the use of biodiesel replaced by diesel.

Hemanth, Prashanth, Benerjee, Choudhuri, and Mrityunjay (2017) generated syngas from jatropha seeds to combine with jatropha biodiesel. Nayak & Mishra (2017) produced this gas and biodiesel from calophyllum inophyllum. Hadkar & Amarnath (2015) synthesized honne biodiesel combining to syngas from coconut shell. Deshmukh, Bhuyar, and Thakre (2008) produced gas and biodiesel from balanites plant. Results from operating under different biodiesel blends and using pure biodiesel combined with syngas on dual fuel mode to compare with these oils only mode 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, Yaliwal et al. (2016) and Hadkar & Amarnath (2015) proofed that the use of pure biodiesel combined to syngas on dual fuel mode had lower engine performance than using both oils only.

Santasnachok et al. (2018) and Srinidhi, Channapatna, Pawar, and Madhusudhan (2016) explained that the calorific value and engine performance were decreased continuously whereas biodiesel was mixed more than 10%. Previous literature reviews mainly focused on biodiesel synthesized from plant oils in those countries and methanol, which was expensive. On the other hand, this research used biodiesel produced from palm oil, which was a year-round economic crop, and ethanol derived from the fermentation of agricultural crops (Sutheerasak & Chinwanitcharoen, 2018). Furthermore, previous researches aimed at the constant syngas flow rate while compressing syngas was mostly combined with diesel on dual fuel (Sutheerasak et al., 2018).

However, the use of diesel and supercharging syngas on dual fuel increased the level of emissions, especially CO, HC, and black smoke, because the amount of oxygen (O_2) required for complete combustion was decreased (Sutheerasak et al., 2018; Das et al., 2012). B10 had the O_2 content which led to more complete combustion although it had lower fuel properties than diesel (Sutheerasak & Chinwanitcharoen, 2018). On the other hand, increasing syngas combined with oils on dual fuel could improve the engine performance (Sutheerasak et al., 2018). The objective of proposed work is to present about the investigation of performance and emissions of a turbocharging diesel engine using B10 combined with supercharging syngas in dual fuel mode to compare with mode of using B10 and diesel only. Syngas was generated from a small downdraft gasifier to have capacity 75 kWth using charcoal in the production process.

Methods and Materials

1. Syngas as a potential fuel for diesel engine

Investigation of performance and emission characteristics of a turbocharging diesel engine from using compressing syngas was carried out at automotive biofuels and combustion engineering research laboratory, Faculty of Engineering, Burapha University, by schematic diagram of experimental setup is shown in Figure 1. Syngas is generated within the gasifier system, which consists of the gasifier, a cyclone, a wet scrubber and a sandbed filter, before it is sent into a Y-shape mixing box and an intake manifold of this engine. Gasifier is the small downdraft gasifier, as specifications are shown in Table 1.

First, charcoal about 10-15 kg from a weighing scale was fed into the gasifier through the top. Air was entranced at the side of this gasifier using a blower to accelerate the reaction time of gasification process, which was investigated from gasification temperature a temperature meter. Next, it was transformed to the hot syngas sent to a cyclone to trap the solid particles. Then, this gas was investigated the flame ability from a flare before it was entered to a wet scrubber to decrease its temperature and tar whereas wet scrubber used the water spray from the top side impinged with the syngas to decrease its temperature and the quantity of tar (Sutheerasak et al., 2018). However, the cooled gas into this scrubber had the humidity in various quantities. To reduce the moistness and keep the pure syngas, it was sent to a sandbed filter tank to clean again while filters consist of sawdust, coarse sand and fine sand respectively as studied from Sutheerasak et al. (2018).

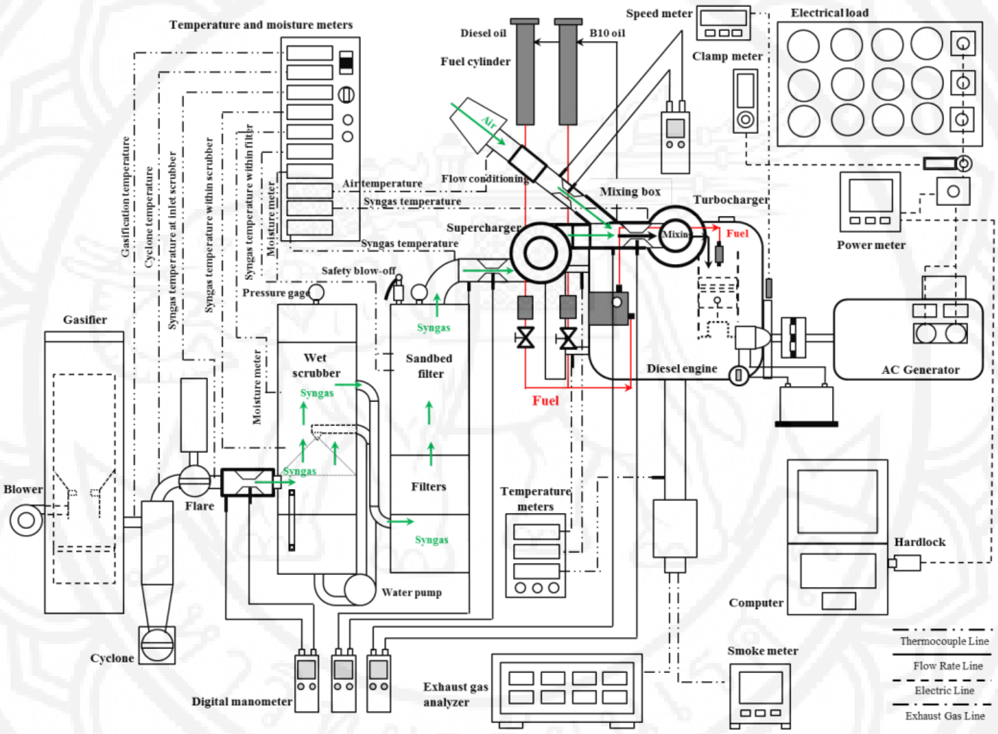

Figure 1 Schematic of the experimental setup

Table 1 Gasifier specification

Item	Description
Type of gasifier	Small downdraft
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

Before syngas was sent into the engine, there was the investigation of various components of syngas to come from the sandbed filter by using a gas chromatography while this gas had the various substances and calorific value which came from the calculation as shown in Table 2. Finally, this gas was compressed by a supercharger, which was a variable speed blower, to increase the gas flow rate sent to a Y-shape mixing box and it was absorbed by a turbocharger of this engine into the combustion chamber. For measuring the flow rate of syngas and air, the flow conditioning was installed before the Y-shape mixing box and a venturi tube and a digital manometer, which was the DT-8890A: differential pressure manometer of CEM Instruments, were applied in this research.

2. Preparation of diesel mixed with 10% biodiesel

First, diesel mixed with 10 % biodiesel (B10) was produced from the reactants, such as diesel and biodiesel which was palm oil ethyl ester synthesized by transesterification process using oleic palm oil and ethanol using sodium hydroxide as discussed in Santasnachok et al. (2018). Ratio of diesel and biodiesel was 90:10 %vol as studied from Sutheerasak & Chinwanitcharoen (2018). Next, there was the investigating properties under various ASTM procedures, such as pour point, cloud point, flash point, fuel density, kinematic viscosity, and lower heating value (LHV) shown in Table 3. Properties of B10 from this research compared to diesel show that flash point increased to 36 °C, fuel density increased to 2.19%, kinematic viscosity increased to 38.97%, and lower heating value decreased to 4.96% respectively.

Table 2 Syngas properties

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
Calorific value (MJ/m^3)	5.08± 0.48

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
Standard diesel from Santasnachok *et al.* (2018)	-	-	52min	810-870	1.80-4.10	-
Diesel	-8.0	7.0	45.0	821	2.90	44.36
B10	-0.5	8.0	81.0	839	4.03	42.16

However, B10 used in this study is compared to B10 from Srinidhi et al. (2016), which produced from 90% diesel and 10% palm oil methyl ester by volume, indicates that flash point increased to 11.7 °C, fuel density increased to 0.24%, kinematic viscosity increased to 9.21%, and lower heating value decreased to 0.095% respectively. Therefore, properties of B10 using in this research is slightly higher than their results, except the heating value.

For applying with diesel engine, B10 produced in this research was compared with characteristics and qualities of standard diesel by Department of Petroleum Business in Thailand (Santasnachok et al., 2018) shown that B10 had the kinematic viscosity and fuel density within the prescribed range and could be applied as a replacement fuel with the diesel engines in the future.

3. 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; capacity 2.9 L; power (max.) 43 kW @ 2,500 rpm; compression ratio 17.2.1; and turbocharger system]. 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 B10 oils to calculate the fuel consumption, 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, MOTORSCAN: 9010 opacity meter/smoke detector was applied in this experiment. Specification of the exhaust gas analyzer is shown in Table 4.

Table 4 Specifications of exhaust gas analyzer

Gas	Measured method	Resolution & Accuracy
CO	IR Bench	0.01± 2%
CO_2	IR Bench	0.01± 2%
HC	IR Bench	1± 2%
Black smoke	Opacity	0.1± 2%

4. Experimental procedure

First, the engine was warmed up about 15-20 min. Room temperature was determined at 33± 2 °C. After engine operation was stable, experiments were started up by using diesel and then B10. In testing, engine speed was started at 1,000± 50 rpm by using the full load and then the speed was increased from 1,200± 50 to 1,600± 50 rpm. The amount of both oils throughout the experiment was determined at 20 ml to investigate the fuel consumption. Final, parameters, such as air flow rate, electrical power, temperatures and emissions, were recorded to compare the use of B10 with diesel.

Next, the B10 and syngas (SG) on dual fuel would be used. Firstly, syngas from gasifier system was sent by supercharger (a blower) at 76 lpm and sent to blend with air in the mixing box. The mixture was, then, sent into the turbocharger, the intake manifold and the combustion chamber of this engine where the B10 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 B10 oils only. They were the flow rates of diesel, B10, syngas and air, the electrical power, the temperatures, the exhaust gas emissions, etc.

After finish using the syngas on duel fuel at a flow rate of 76 lpm, others flow rates of the syngas would, then, be introduced and the same conditions and parameters would be recorded. All the syngas flow rates used in this study were 76, 79, 85, 93, 103, 116, and 125 lpm, and terms of B10 combined with syngas flow rate (B10+SG) from 76 to 125 lpm were demonstrated as B10+SG76 lpm, B10+SG79 lpm, B10+SG85 lpm, B10+SG93 lpm, B10+SG103 lpm, B10+SG116 lpm and B10+SG125 lpm. When all period of the engine tests were between 50 to 100 hours (Sutheerasak et al., 2018), all experiments from using dual fuel and both oils were applied for analyzing the engine performance characteristics. In this research, the power output is shown in value of the electrical power. Engine performance analysis was determined from mean effective pressure, electrical efficiency, specific energy consumption and fuel consumption rate as studied from Sutheerasak et al. (2018).

Results

Results of engine performance and emissions test from using dual fuel to compare with only diesel and B10 oils are depended on the mean effective pressure (MEP), which calculated from the multiplication of electrical power at engine speed from 1,000 to 1,600 rpm and the number of revolutions per power stroke divided by the multiplication of displacement volume and these speed, shown in Figure 2. It indicates that the electrical power and the MEP increase with increasing engine speed at 1,000, 1,200, 1,400 and 1,600 rpm. Electrical power increased at 8.81±0.005, 12.67±0.018, 15.85±0.004 and 20.28±0.005 kW_e, whereas MEP increased at 10.73±0.017, 12.52±0.013, 13.99±0.027 and 15.61±0.089 bar respectively.

Figure 3 observes the electrical efficiency calculated from the ratio of the electrical power output and the total energy input. Electrical efficiency changes with increasing syngas and MEP, and the maximum electrical efficiency occurred at 13.99 bar of MEP by using speed 1,400 rpm. Electrical efficiency from using Diesel, B10, B10+SG76 lpm, B10+SG79 lpm, B10+SG85 lpm, B10+SG93 lpm, B10+SG103 lpm, B10+SG116 lpm, B10+SG125 lpm, and diesel combined with syngas at 125 lpm (Diesel+SG125lpm) equaled 27.61, 26.32, 26.78, 27.78, 28.16, 28.87, 29.53, 30.31, 30.90, and 32.23 % respectively.

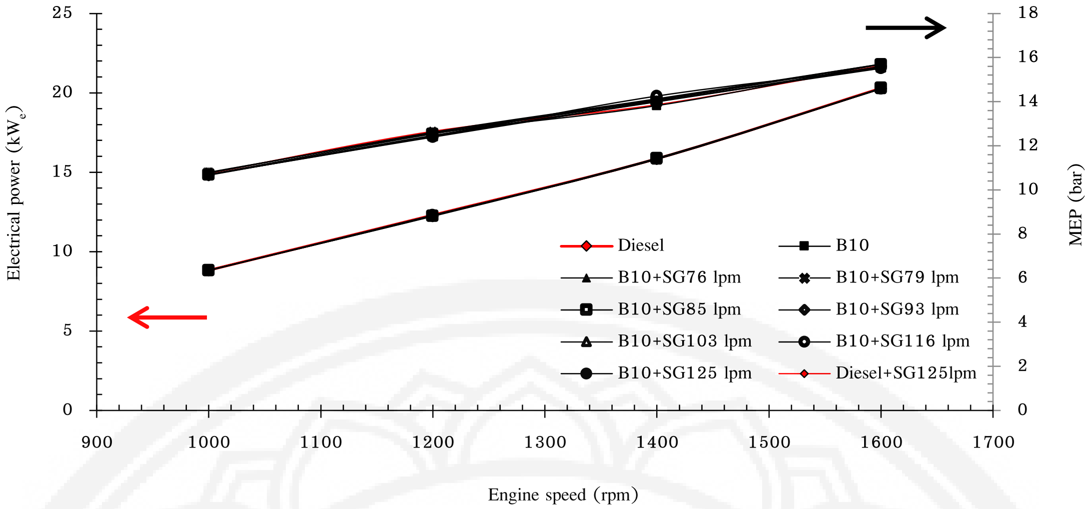

Figure 2 Electrical power and MEP with various engine speeds

The variation between specific energy consumption (SEC) with various gas flow rates and MEP is shown in Figure 4. The SEC was calculated from the ratio of the total energy input to come from fuel consumption rate and fuel calorific value and the electrical power output at full load. SEC changes with increasing syngas and MEP, whereas the minimum SEC occurred at 13.99 bar of MEP by using speed 1,400 rpm. SEC from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 13.04, 13.68, 13.44, 12.96, 12.78, 12.47, 12.19, 11.88, 11.65, and 11.17 MJ/kW_e.hr respectively.

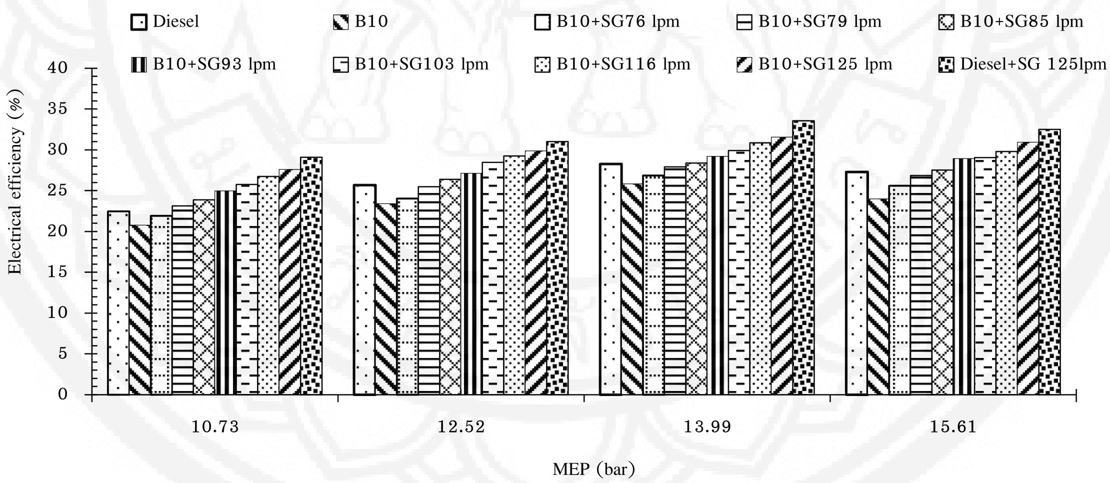

Figure 3 Electrical efficiency with various MEP

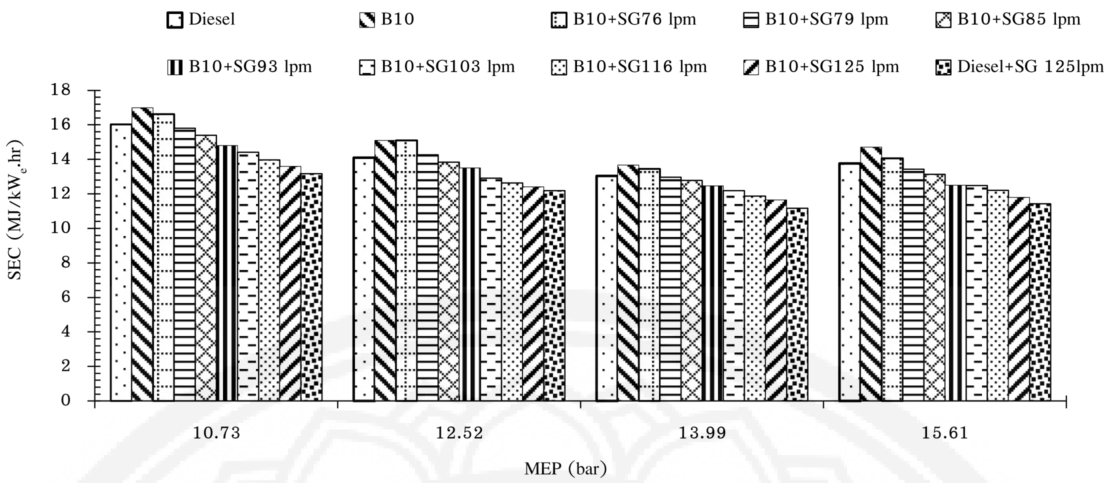

Figure 4 SEC with various MEP

As shown in Figure 5, results of the fuel consumption rate (FCR) increases with increasing MEP but it decreases with increasing syngas. At 13.99 bar of MEP by using speed 1,400 rpm, FCR from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 5.68, 6.13, 5.78, 5.56, 5.45, 5.27, 5.11, 4.94, 4.81, and 4.47 lph respectively. In case of exhaust gas temperature (EGT) trends increased with increasing gas flow rate and MEP shows in Figure 6. To consider at 13.99 bar of MEP by using speed 1,400 rpm, EGT from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 139.27, 151.25, 190.18, 208.15, 213.14, 220.13, 229.12, 234.61, 244.09, and 258.13 °C respectively.

Since the release of carbon dioxide (CO_2) extremely effects on the global warning and greenhouse effect, it is necessary to measure the CO_2 emission from this engine. As indicated in Figure 7, the release of CO_2 is increased with increasing syngas and MEP. At 13.99 bar of MEP by using speed 1,400 rpm, CO_2 emissions from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 6.23, 7.08, 8.18, 8.52, 8.86, 9.28, 9.54, 10.33, 10.67, and 11.08 %vol respectively.

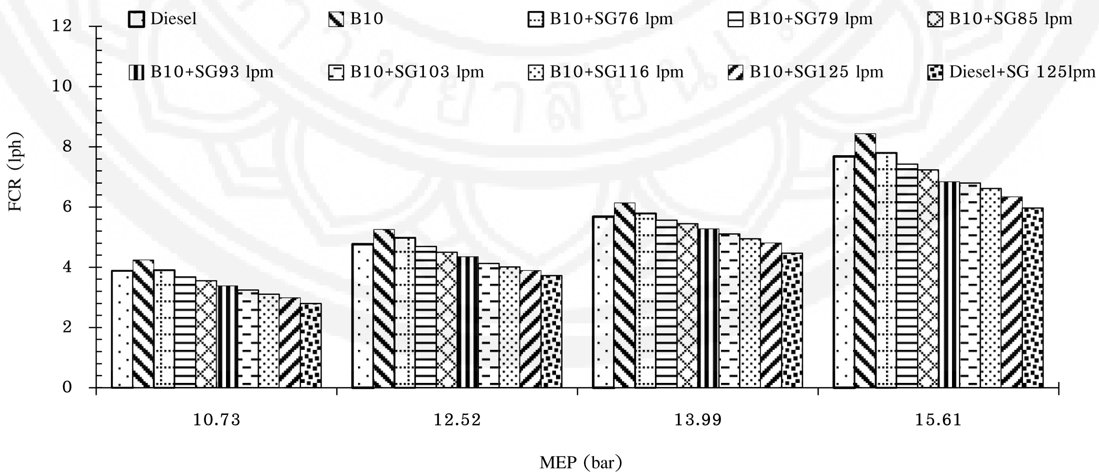

Figure 5 Fuel consumption rate with various MEP

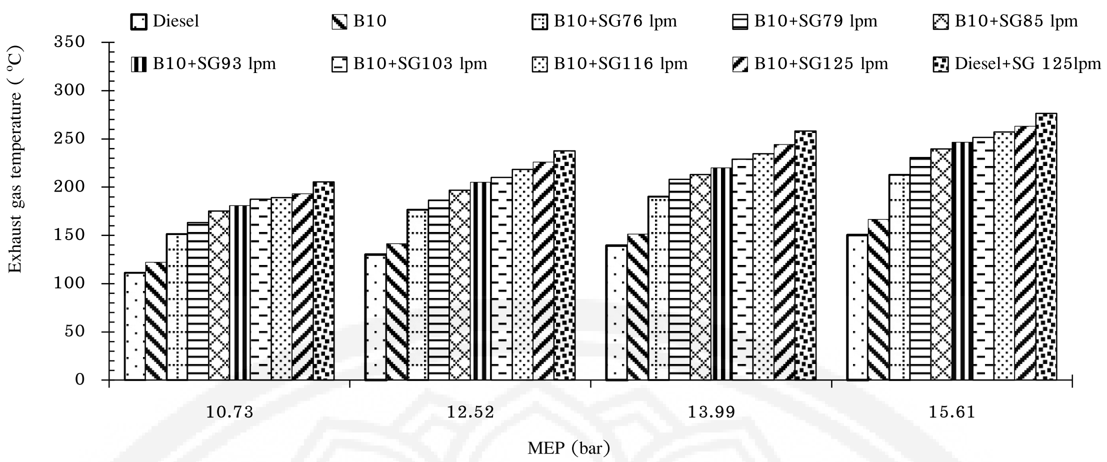

Figure 6 Exhaust gas temperatures with various MEP

Trends of the carbon monoxide (CO) emission are shown in Figure 8. It is evident from the figure that, the amount of CO decreases with increasing MEP but it increases with increasing syngas. At 13.99 bar of MEP by using speed 1,400 rpm, CO emissions from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 0.20, 0.11, 0.55, 0.61, 0.65, 0.70, 0.75, 0.82, 0.87, and 0.93 %vol respectively. The emission of hydrocarbon (HC) with varying MEP from using the dual fuel and only DEB and diesel oils are presented in Figure 9. HC emission increases with increasing syngas and MEP. At 13.99 bar of MEP by using speed 1,400 rpm, HC emissions from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 19.81, 14.38, 27.13, 29.44, 32.31, 35.88, 40.44, 44.31, 47.50, and 58.12 ppm respectively.

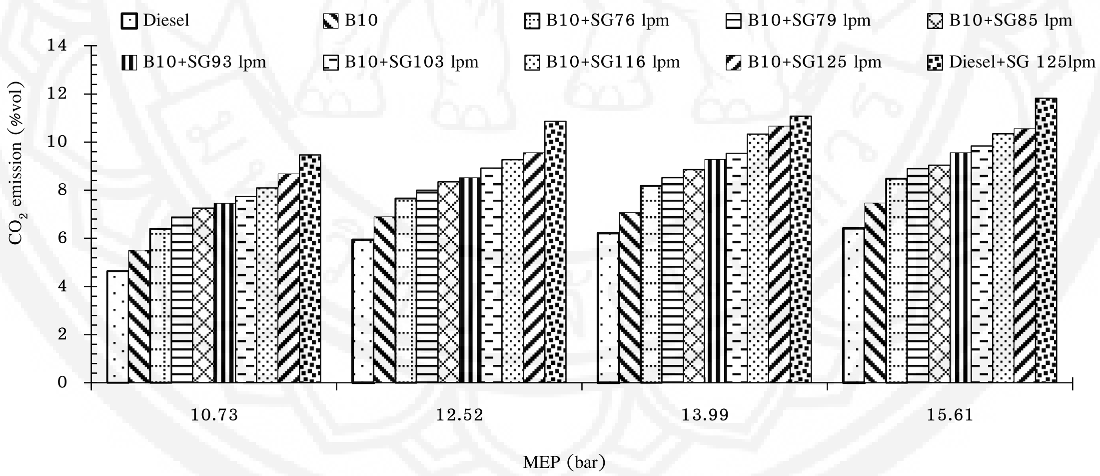

Figure 7 Carbon dioxide levels at various MEP

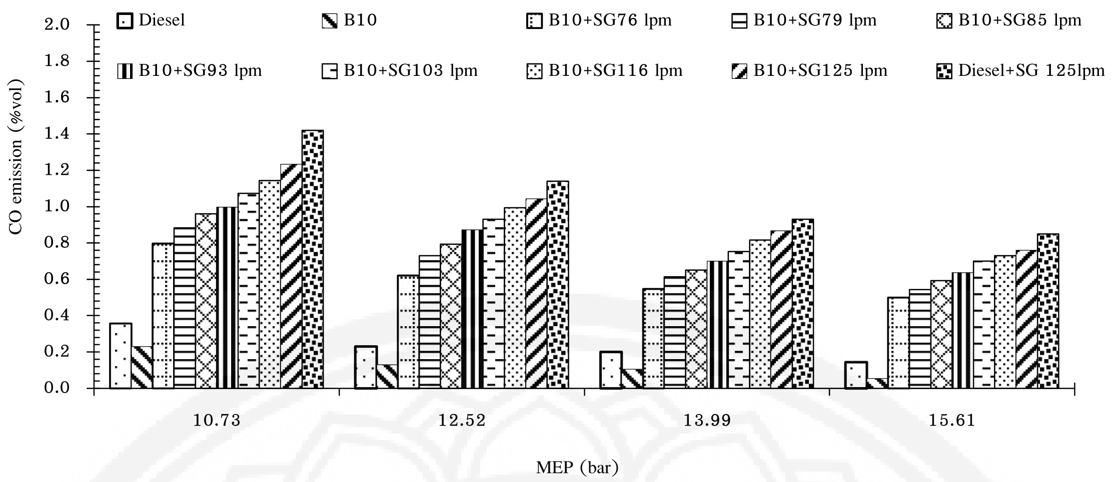

Figure 8 Carbon monoxide levels at various MEP

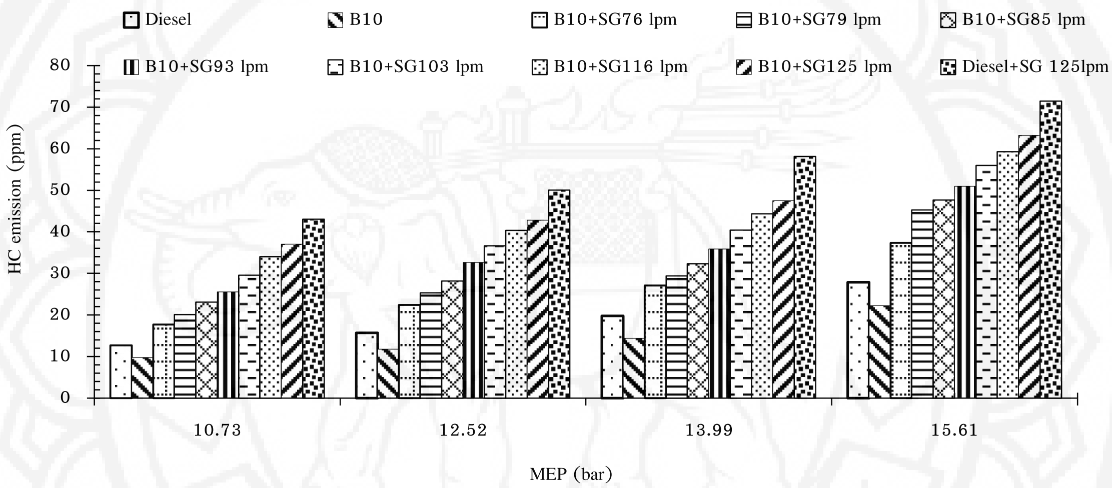

Figure 9 Hydrocarbon levels at various MEP

Finally, black smoke is a part of particulate matter that is resulted from a mass of impure carbon particles resulting from the incomplete combustion of hydrocarbons. This research investigates the black-smoke release from the smoke opacity shown in Figure 10. Black-smoke release trends increase with increasing syngas and MEP. At 13.99 bar of MEP by using speed 1,400 rpm, the smoke opacity from using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm equaled 1.99, 1.72, 2.36, 2.47, 2.62, 2.79, 3.02, 3.22, 3.58, and 4.32 K/m respectively.

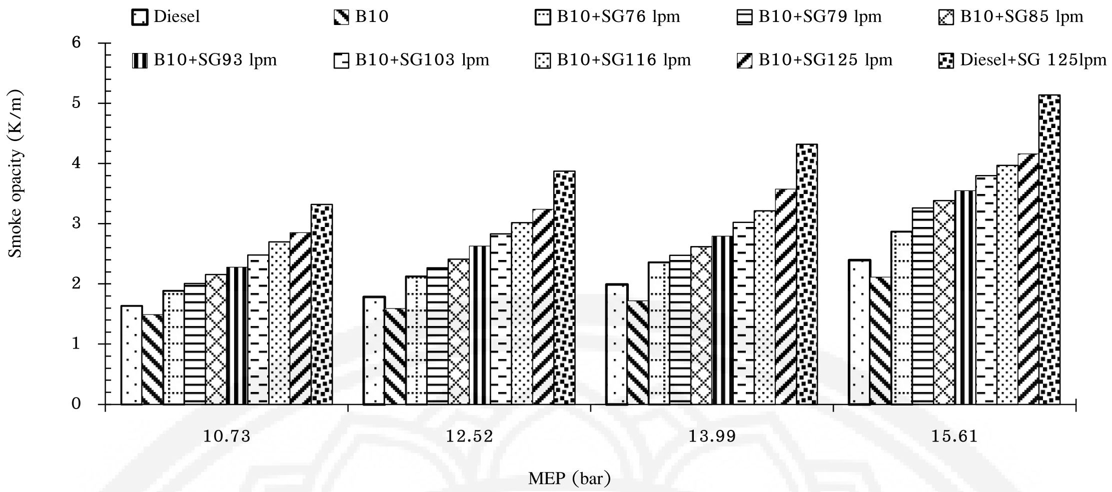

Figure 10 Smoke levels at various MEP

Discussion

From various results of engine testing, using Diesel, B10, B10+SG from 76 to 125lpm and Diesel+SG125lpm have changed the engine performance and various emissions, such as CO_2, CO, HC, and black smoke, described below.

1. Electrical efficiency

Use of B10 observes that electrical efficiency was decreased to 1.29% as compared with diesel, and it was decreased to 0.18% as compared with Srinidhi et al. (2016). These results are consistent with Sutheerasak & Chinwanitcharoen (2018) since B10 had higher fuel density and lower heating value than diesel (Table 3) led to increase of fuel consumption and decrease of electrical efficiency. Next, syngas is combined with the B10 on dual fuel by compressing syngas, which was the increase of syngas flow rate from 79 to 125 lpm. While they are compared with using B10 and diesel only, electrical efficiency increases with increasing syngas (Figure 3). To compare with using B10 only at maximum efficiency, the use of B10 and supercharging syngas from 79 to 125 lpm on dual fuel had the electrical efficiency to increase from 0.46 to 4.58 % and up to 3.30 % compared to diesel only. Results of this research have higher efficiency than Hemanth et al. (2017) and Nayak & Mishra (2017), but they are consistent with the results of Sutheerasak et al. (2018). It is caused by this research applies the supercharger to increase gas flow rate combined with turbocharger system of this engine, which led to better combustion of relatively rich syngas-air mixture affected on quickly premixed combustion phase and better combustion from concentration of O_2 within B10 and syngas on dual fuel resulting in reduced requirement of total energy input. Moreover, increasing syngas led to decrease of the pilot B10 quantity affected on the reduction of total energy input. These reasons lead to increase of electrical efficiency.

This research indicates that the electrical efficiency from using B10+SG at 85 lpm on dual fuel is similar to using diesel because the use of syngas flow rate at 85 lpm mixed to air combining to B10 could decrease the pilot B10 quantity due to better combustion. Use of syngas combined to B10 led to the start of combustion quickly, and it resulted in improved combustion characteristics and closed to using diesel (Nayak & Mishra, 2017; Hemanth et al., 2017). However, the electrical efficiency from using B10+SG at 125 lpm on dual fuel is the best because the increase of syngas quantity up to 125 lpm had a very high fuel replacement which led to the decrease of total energy input very much (Sutheerasak et al., 2018). In case of using B10+SG at 125lpm compared with using Diesel+SG at 125lpm on dual fuel demonstrating the electrical efficiency lower than 1.32 %. This is similar to result of Hemanth et al. (2017) and Nayak & Mishra (2017), because B10 had lower calorific value and higher viscosity than diesel leading to advanced injection timing and poor atomization resulting in an inferior combustion.

2. Specific energy consumption

The SEC from using B10 was higher as increased to 4.88 % compared with diesel at maximum efficiency. This result is consistent with the result of Sutheerasak & Chinwanitcharoen (2018) explained by B10 was lower fuel heating value than diesel which led to increase of fuel consumption. As compressing syngas combined with B10 on dual fuel to compare with using B10 and diesel only, the SEC decreased with increasing syngas. To compare with using B10 only, the SEC decreased from 1.72 to 14.83 % and it reduced to 10.67 % compared to diesel. Results of this research have lower SEC than Hemanth et al. (2017) and Nayak & Mishra (2017) but they are similar to the results of Sutheerasak et al. (2018), because the increase of syngas by driving compressor and turbocharger system led to decrease of pilot B10 as explained in the previous section.

Similarly, this research shows that the SEC from using B10+SG at 85 lpm on dual fuel is similar to using diesel because the use of B10+SG at 85 lpm in dual fuel mode had decreased the pilot B10 quantity which resulted in the total energy input equaled to using diesel (Nayak & Mishra, 2017; Hemanth et al., 2017). Moreover, the SEC from using B10+SG at 125 lpm in dual fuel mode is the lowest, because the total energy input was decreased very much as explained in the section of the electrical efficiency. Using B10+SG at 125 lpm compared with Diesel+SG at 125 lpm proves that the SEC was higher than 4.28 %. This is consistent with the results of Hemanth et al. (2017) and Nayak & Mishra (2017) because B10 was lower fuel heating value than diesel. In addition, the SEC was the opposite effect on electrical efficiency as the using Diesel+SG at 125 lpm was higher electrical efficiency than B10+SG at 125 lpm. At a result, SEC from using Diesel+SG at 125 lpm is lower than that of B10+SG at 125 lpm also.

3. Fuel consumption rate

For using B10 compared with diesel, the FCR increased to 7.92 % at maximum efficiency. It is concluded that using B10 consumes more fuel than diesel agreed to Sutheerasak & Chinwanitcharoen (2018) since the B10 was lower calorific value than diesel. In case of using B10 and compressing syngas on dual fuel compared with the use of only both oils are demonstrated that the FCR was decreased with increasing syngas. Use of supercharging syngas combined to B10 on dual fuel compared with using B10 only at maximum efficiency indicates that the FCR decreased from 5.70 to 21.58 % and it reduced to 15.36 % compared to diesel. Results of this work have lower FCR than Hemanth et al. (2017) and Nayak & Mishra (2017), but they are similar to the results of Sutheerasak et al. (2018). Because the use of B10 combined with increasing syngas quantity had the start of ignition faster, it led to the opening and closing of needle lift within an injector quickly. This reason led to the reduction of pilot B10 quantity. Therefore, using B10 and compressing syngas on dual are more fuel saving than using both oils only.

Identically, this research found that most fuel saving occurred from using B10+SG at 125 lpm at 10.73 bar of MEP by the fuel saving was increased to 29.63 % and 23.21 % to compare with the use of only B10 and diesel respectively. Therefore, the use of B10+SG at 125 lpm in dual fuel mode has the highest fuel saving. As compared with using diesel only, the use of B10+SG at 85 lpm has similar fuel consumption rate to using diesel only because this gas flow rate combined to B10 helps to decrease the consumption of B10 (Nayak & Mishra, 2017; Hemanth et al., 2017). Comparing B10+SG at 125 lpm with Diesel+SG at 125 lpm found that the FCR from using B10+SG at 125 lpm was higher than 7.68 % as contrasted to Hemanth et al. (2017) and Nayak & Mishra (2017), because B10 had lower calorific value and higher fuel viscosity than diesel which led to the increase of fuel consumption (Sutheerasak & Chinwanitcharoen, 2018).

4. Exhaust gas temperature

In case of the use of B10 compared to diesel, the EGT from using B10 was higher as increased to 11.98 ^{o}C at maximum efficiency and it was decreased to 8.02 ^{o}C as compared with Srinidhi et al. (2016). Results are consistent with Sutheerasak & Chinwanitcharoen (2018) since the concentration of O_2 within B10 led to more complete combustion resulting in higher combustion temperature until the exhaust valve was opened. Using B10 and supercharging syngas on dual fuel compared with B10 and diesel only indicates that the EGT increased with increasing syngas and MEP. To investigate at maximum efficiency, the EGT increased from 38.94 to 92.85 ^{o}C and 50.92 to 104.83 ^{o}C respectively. Results are consistent with Nayak & Mishra (2017), Yaliwal et al. (2016) and Sutheerasak et al. (2018) explained from the syngas properties which had the CO_2 and CO contents (Table 2), while it was combined to B10 burned with O_2 content within a combustion chamber. It had changed the combustion phenomena in the diffusion combustion phase, which led to an increase in the late combustion period. It was burned continuously until the exhaust valve is opened.

While the use of B10+SG at 85 lpm was compared with using B10 and diesel only, the EGT increased to 61.89 and 73.87 ^{o}C respectively. However, the use of B10+SG at 85 lpm has a lower level of EGT than using B10+SG at 125 lpm. Therefore, the use of gas flow rate at 85 lpm on dual fuel is better because the level of EGT is lower which lead to a decrease the various emissions as explained in the next section. For using B10+SG at 125 lpm compared with Diesel+SG at 125 lpm, it was lower EGT as decreased to 14.04 ^{o}C. Because B10 had the molecular carbon, hydrogen and oxygen (C-H-O), it was combined with syngas led to better combustion and then there was the reduction of late combustion (Whitty, Zhang, & Eddings, 2008).

5. Carbon dioxide emission

Using B10 compared to diesel demonstrating that the CO_2 emission was increased to 0.85 %vol at maximum efficiency. As consistent with Sutheerasak & Chinwanitcharoen (2018), it is explained by the concentration of O_2 within B10 led to more complete combustion. The amount of C from this oil was reacted with more O_2 which led to higher release of CO_2. Compressing syngas combined to B10 compared with using B10 and diesel only shows that the release of CO_2 was increased with increasing syngas and MEP. At maximum efficiency, CO_2 emission was increased from 1.11 to 3.60 %vol and 1.96 to 4.45 %vol respectively. Comparing B10+SG125 lpm with a result of Nayak & Mishra (2017) indicates that there was the release of CO_2 increased to 4.87 %vol because the syngas quantity in this work was higher. Results of this research are consistent with Sutheerasak et al. (2018) and Rith, Biona, Gitano-Briggs, and Sok (2016) because the generated syngas consisted of both CO and CO_2 quantities (Table 2). While the increase of syngas flow rate up to 125 lpm combined to B10 reacted with O_2 content within the combustion chamber, innumerable contents of C were burned with high O_2 content which came from the composition of air and B10. As a result, there was an increase in combustion temperature and the steep rise in the release of CO_2 as corresponding to the increasing trend of the exhaust gas temperature.

To investigate the CO_2 emission from using B10+SG at 85 lpm compared with using B10 and diesel only, the level of CO_2 increased by only 1.78 and 2.63 %vol respectively. Use of B10+SG at 85 lpm has a lower CO_2 release than using B10+SG at 125 lpm. Therefore, the ability in applying syngas combined to B10 on dual fuel should use the syngas content not more than 85 lpm. Although B10+SG at 85 lpm will give the engine performance and fuel saving lower than using B10+SG at 125 lpm, it has similar engine performance to using diesel only. Besides, it helps to reduce the disadvantage of high fuel consumption while B10 is applied for renewable fuel. For using B10+SG at 125 lpm compared with Diesel+SG at 125 lpm, CO_2 emission was decreased to 0.41 %vol. This is consistent with Hemanth et al. (2017) and Nayak & Mishra (2017), because B10 contained the C-H-O molecules as combined with syngas led to the more complete combustion than the use of diesel and syngas on dual fuel. Moreover, it is also confirmed that B10 has lower C/H ratio than diesel (Srinidhi et al., 2016). Although there was the increase of syngas combined to B10, it helped in the reduction of late combustion period and burning temperature. Both reasons led to the lower release of CO_2 (Whitty et al., 2008).

6. Carbon monoxide emission

Using B10 reduced CO emission to 0.09 %vol compared to diesel at maximum efficiency. This is consistent with Sutheerasak & Chinwanitcharoen (2018), because the formation of CO depended on the amount of O_2 required for combustion reaction, B10 had the O_2 element enhanced the combustion reacting with C molecules led to more release of CO_2. At a result, there was the decrease of CO emission. As compared with a result of Srinidhi et al. (2016), B10 of this research had higher CO emission since biodiesel, used in blending, was produced from ethanol leading to poor atomization resulting in the incomplete combustion as discussed in Venkateswara (2016). However, Figure 8 shows that the increasing syngas to combine with B10 compared with B10 and diesel only demonstrates higher level of CO than the use of both oils only. At maximum efficiency, CO emission was increased from 0.44 to 0.76 %vol and 0.35 to 0.67 %vol respectively, while results are consistent with Hemanth et al. (2017), Nayak & Mishra (2017) and Whitty et al. (2008) since increasing syngas caused to high incomplete combustion. Although syngas had a much wider ignition range than the normal oil, it could be burned leaner, reducing CO emission over levels obtained from burning normal oil, this might be due to the presence of CO which was the highest quantity (Table 2), except N_2, of the syngas compositions. The more syngas was compressed to the intake manifold, the less of air flow to the engine as well as the amount of O_2 required for complete combustion decreased with increasing syngas (Garcia-Armingol & Ballester, 2015). The presence of CO in syngas, duel fuel operations resulted significant increased the CO emission as compare to both oils. Overall emissions of CO for all B10+SG increase with the increase of syngas.

However, this research indicates that the use of B10+SG at 85 lpm compares with using B10 and diesel only, the level of CO increased by only 0.54 and 0.45 %vol respectively. Use of B10+SG at 85 lpm could decrease the release of CO more than using B10+SG at 125 lpm, while the use of B10+SG at 125 lpm has the more release of CO because there is the incomplete combustion from highly syngas quantity. When using B10+SG at 125 lpm compared with Diesel+SG at 125 lpm, it produced low CO emission as decreased to 0.06 %vol. Results are consistent with Hemanth et al. (2017) and Nayak & Mishra (2017) because the B10 consists of the C-H-O molecules and the extra O_2 elements enhanced the combustion reacting with C molecules. This reaction, then, reduced CO emission better than using Diesel+SG on dual fuel.

7. Hydrocarbon emission

HC emission from using B10 decreased to 5.44 ppm compared to diesel at the maximum efficiency. This is consistent with Sutheerasak & Chinwanitcharoen (2018) since the presence of O_2 in B10 which improved the burning quality in the combustion chamber led to more complete combustion than diesel. The trends of HC emission from the supercharging syngas combined to B10 found that HC emission increases as increasing gas flow rates. Compressing syngas and B10 on dual fuel compared with B10 and diesel only at maximum efficiency shows that HC emission increased from 12.75 to 33.13 ppm and 7.31 to 27.69 ppm, respectively, while they are consistent with Nayak & Mishra (2017). The cause of increasing HC emission is explained from the direct result of incomplete combustion because the syngas contains the innumerable molecules of C and H. The high syngas content in combining to B10 injection will result in the less amount of O_2. Therefore, the greater insufficient amount of O_2 will increase the CO and HC emission. Next, the chemical reaction between dual fuel and O_2 content, which was decreased as increasing syngas, 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 reacted with many of the C and H molecules leading to their incomplete combustion. At a result, there is the formation of undesirable combustion products, especially the HC and CO emissions (Whitty et al., 2008).

However, the use of B10+SG at 85 lpm has lower level of HC than using B10+SG at 125 lpm. HC emission from using B10+SG at 85 lpm as compared with using B10 and diesel only has the release of HC increased by only 17.93 and 12.50 ppm respectively. Therefore, the use of B10+SG at 85 lpm could decrease the release of HC more than using B10+SG at 125 lpm because of lower incomplete combustion. In Figure 9, the release of HC from using B10+SG at 125 lpm was 10.62 ppm lower than the duel fuel of Diesel+SG at 125 lpm while this result is similar to Hemanth et al. (2017) and Nayak and Mishra (2017). It is caused by B10 had the O_2 elements enhanced the combustion reacting with C and H molecules to produce the CO_2 and H_2O highly. On the other hand, diesel was the C and H molecules whereas increasing syngas led to decrease of O_2 content affected on the formation of HC emission highly (Whitty et al., 2008).

8. Black smoke level

Using B10 compared to diesel indicates that smoke opacity decreased to 0.27 K/m. This result is consistent with Sutheerasak & Chinwanitcharoen (2018) because of the O_2 content in B10 enhanced combustion during diffusion combustion which subsequently reduced the smoke density. Increasing syngas quantity combined to B10 compared with using B10 and diesel only indicates that the smoke opacity increased as increasing syngas and MEP. Figure 10 demonstrates that using B10 and compressing syngas on dual fuel led to high level of black smoke. As compared to using B10 and diesel only at maximum efficiency, smoke opacity increased from 0.64 to 1.86 K/m and 0.37 to 1.58 K/m respectively. Results had higher smoke opacity than the result of Nayak & Mishra (2017) because this research used more syngas quantity than. However, these results are similar to Sutheerasak et al. (2018) because of the greater amount of C molecules from the increasing syngas content while decreasing the amount of O_2 due to reducing the air entrance. The smoke opacity shows the consistency trend of higher level of CO and HC emissions (Whitty et al., 2008).

To consider using B10+SG at 85 lpm as compared with using B10 and diesel only, the smoke opacity increased by only 0.90 and 0.63 K/m respectively. Use of B10+SG at 85 lpm releases the smoke density lower than using B10+SG at 125 lpm. From investigating the results of various emissions, such as CO_2, CO, HC, and smoke density, they are confirmed that the increase of syngas content up to 125 lpm combining to B10 on dual fuel has highly tremendous pollutants. Therefore, the use of syngas combining to B10 in dual fuel mode should use the syngas quantity not more than 85 lpm to decrease the more incomplete combustion which leads to the increase of these emissions. While using B10+SG at 125 lpm compared with Diesel+SG at 125 lpm, it had lower smoke opacity as decreased to 0.743 K/m. This result is similar to Hemanth et al. (2017) and Nayak & Mishra (2017), because the B10 possessed more O_2 molecules that improved better combustion although combined with syngas. It, then, led to more complete combustion than the use of diesel and syngas on dual fuel.

Conclusion and Suggestions

The turbocharging diesel engine test using dual fuel of B10 and supercharging syngas has been studied. The critical findings are listed below.

1. Results from the engine test using B10 compared with diesel indicates that B10 has a slight decrease in electrical efficiency and the little increase of SEC and fuel consumption because of lower calorific value and higher fuel viscosity. On the other hand, various emissions, such as CO, HC, and black smoke, are decreased because of the concentration of O_2 within B10 oil led to more complete combustion. It can be applied as a replacement fuel with the diesel engines for the locomotives and automobiles in the future.

2. Engine-performance results from using B10 and supercharging syngas in dual fuel mode show that the use of B10+SG at 125 lpm is the best because the use of syngas flow rate at 125 lpm on dual fuel can replace more B10 very much which lead to more fuel saving and increasing electrical efficiency. Another advantage is that it can increase the high syngas quantity which lead to the developing syngas for diesel engines without B10 or diesel to help to burn in the future. However, the disadvantage of using B10+SG at 125 lpm is that various emissions are enormously increased. Therefore, the syngas properties, especially CO_2 and CO contents, should be reduced to lead to ability in using high syngas content combined to B10 or diesel in dual fuel mode.

3. Use of B10+SG at 85 lpm can reduce the various pollutants by up to 50% as compared with using B10+SG at 125 lpm. Therefore, the ability in applying syngas combined to B10 on dual fuel should use the syngas content not more than 85 lpm. The disadvantage of using B10+SG at 85 lpm is that the engine performance and fuel saving were lower than using B10+SG at 125 lpm, but it has similar engine performance to using diesel only. In addition, it helps to reduce the disadvantage of high fuel consumption while B10 is applied for renewable fuel.

4. Comparison between using B10+SG at 125 lpm with Diesel+SG at 125 lpm confirms that the use of Diesel+SG at 125 lpm has higher engine performance than using B10+SG at 125 lpm because diesel has higher calorific value than B10, but it releases higher various emissions than using B10+SG at 125 lpm. Therefore, using B10+SG at 125 lpm can reduce more various emissions than using Diesel+SG at 125 lpm. If compositions within syngas can limits the CO_2 and CO contents, using B10+SG at 125 lpm will be the best choice.

To further improve the present system, the following suggestions can be adopted in the future:

1. Study of combustion characteristics and other emissions, especially formation of nitrogen oxides (NOx) and particulate matter from using B10 and compressing syngas on dual fuel mode.

2. Study of engine wear from using B10+SG at 85 lpm on dual in the long term because of this mixture ratio can give the engine performance close to the use of diesel only.

3. Using supercharged air combined with compressed syngas to improve engine performance and to decrease emissions, such as CO and HC emissions.

4. Study of using other biomasses to produce the syngas fuel and decreasing CO2 and CO contents within the syngas composition to reduce the various emissions as combined to B10 in dual fuel mode.

5. Modification of the diesel engine by adjusting the injection timing to decrease the pilot B10. In addition, development of the exhaust gas recirculation (EGR) system to apply with the dual fuel mode to reduce the various emissions of diesel engine.

Acknowledgments

The authors acknowledge the financial support from the Faculty of Engineering (grant no. 9/2552), Burapha University, Thailand. Also, the authors thank Mr. Apisak Jiw, Mr. Kittiwat Nukul, and Mr. Wittaya Boonmak for their help in data collecting to complete this study.

References

Das, D. K., Dash, S. P., & Ghosal, M. K. (2012). Performance evaluation of a diesel engine by using producer gas from some under-utilized biomass on dual-fuel mode of diesel cum producer gas. *Journal of Central South University, 19*(6), 1583-1589.

Deshmukh, S. J., Bhuyar, L. B., & Thakre, S. B. (2008). Investigation on performance and emission characteristics of ci engine fuelled with producer gas and esters of hingan (balanites) oil in dual fuel mode. *International Journal of Aerospace and Mechanical Engineering, 2*(3), 148-153.

Hadkar, T., & Amarnath, H. K. (2015). Performance and emission characteristics of producer gas derived from coconut shell (biomass) and honne biodiesel with different configuration of carburetor for dual fuel four stoke direct injection diesel engine. *Engineering and Applied Science Research (EASR), 2*(3), 1804-1811.

Hemanth, G., Prashanth, B., Benerjee, N., Choudhuri, T., & Mrityunjay, M. (2017). Dual fuel mode operation and its emission characteristics in diesel engine with producer gas as primary fuel and jatropha biodiesel as pilot fuel. *International Journal of Mechanical Engineering and Technology, 8*(4), 138-147.

Nayak, S. K., & Mishra, P. C. (2017). Emission from a dual fuel operated diesel engine fuelled with calophyllum inophyllum biodiesel and producer gas. *International Journal of Automotive and Mechanical Engineering, 14*(1), 3954-3969.

Rith, M., Biona, J. B. M., Gitano-Briggs, H. W., & Sok, P. (2016). Performance and emission characteristics of the genset fuelled with dual producer gas-diesel. *Proceedings of the DLSU Research Congress 2016, 7-9 March 2016* (pp. 1-7). Manila, Philippines: De La Salle University.

Santasnachok, M., Sutheerasak, E., Ruengphrathuengsuka, W., & Chinwanitcharoen, C. (2018) Performance analysis of a diesel-engine generator using ethyl ester synthesized from anhydrous ethanol and NaOH. *International Journal of Electrical and Electronic Engineering & Telecommunications, 8*(2), 108-112.

Srinidhi, C., Channapatna, S. V., Pawar, A. A., & Madhusudhan, A. (2016). Performance and emissions of diesel engine fuelled with ethanol and palm oil methyl ester. *International Research Journal of Engineering Technology, 3*(4), 108-113.

Sutheerasak, E., & Chinwanitcharoen, C. (2018). Performance and emissions of a diesel engine using palm ethyl ester. *Engineering Journal Chiang Mai University, 25*(2), 1-13.

Sutheerasak, E., Pirompugd, W., & Sanitjai, S. (2018). Performance and emissions characteristics of a direct injection diesel engine from compressing producer gas in a dual fuel mode. *Engineering and Applied Science Research, 45*(1), 47-55.

Venkateswara, R. P. (2016). Performance analysis of ci engine fuelled with diesel-biodiesel (methyl/ethyl esters) blend of non-edible oil. *International Journal of Research-Granthaalayah, 4*(7), 20-26.

Vieira da Silva, M. A., Ferreira, B. L. G., Marques, L. G. C., Murta, A. L. S., & Vasconcelos de Freitas, M. A. (2017). Comparative study of NO_x emissions of biodiesel-diesel blends from soybean, palm and waste frying oils using methyl and ethyl transesterification routes. *Fuel, 194,* 141-156.

Yaliwal, V. S., Banapurmath, N. R., Revenakar, S., & Tewari, P. G. (2016). Effect of mixing chamber or carburetor type on the performance of diesel engine operated on biodiesel and producer gas induction. *International Journal of Applied Engineering and Technology, 5*(2), 25-37.

Whitty, K., Zhang, H., & Eddings, E. (2008). Emissions from syngas combustion. *Journal of Computer Science and Technology, 180*(6), 1117-1136.