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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Comparative investigation of using DEB oil and supercharging syngas and DEB oil as a dual fuel in a DI diesel engine

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Received 9 July 2018
Revised 25 September 2018
Accepted 27 September 2018

Abstract

Improving diesel oil properties for the reduction of hazardous pollution and decreasing depletion of petroleum liquid fuel leads to the use of alternative fuels, especially ethanol and syngas fuels, developed for use in diesel engines. This research aims to investigate the effects of using diesel oil mixed with ethanol and emulsified butanol oil (DEB oil) and dual fuel (supercharged syngas combined with DEB oil) on engine performance and emissions in a three-cylinder direct injection (DI) diesel engine. The engine was connected to a generator and tested at various speeds at full load. The results of using DEB oil compared to diesel oil showed that it had fuel properties similar to diesel oil, with better engine performance and reduced pollution emissions, i.e., CO_2, CO, and black smoke. Syngas was generated with a downdraft gasifier using charcoal. It was compressed to increase the gas flow rate from 76 to 125 lpm, combined with DEB oil and used as dual fuel. The results of engine testing compared DEB alone and diesel oils. They indicated that DEB oil and supercharged syngas as a dual fuel had higher engine performance. Moreover, compressing syngas at 125 lpm compared with using DEB oil alone at an engine speed 1600 rpm and full load found that the fuel-savings increased by 25.85% and 23.53%, respectively. Conversely, some emissions were greatly increased with greater syngas quantities and engine speeds.

Keywords: DEB oil, Supercharged syngas, Diesel engine, Performance, Emissions

1. Introduction

Ethanol is an alternative fuel developed for diesel engines to decrease primary pollutants, such as carbon monoxide (CO), hydrocarbons (HC) and black smoke. It can be produced from edible and non-edible plants and has an oxygen (O_2) content. When mixed with diesel fuel, better combustion can result [1-2]. Moreover, ethanol be fermented from many agricultural plants in Thailand. To use ethanol in diesel engines, Kumar et al. [2] discussed blending diesel oil with ethanol and emulsifiers, a substance that acts as a stabilizer, preventing liquids that ordinarily did not mix from separating. This is called DE oil. Such material has the best stability and does not require modification of the injection and induction systems for complete combustion as would be required for diesel oil.

Researchers [1-5] have discussed the use of DE oil, which is 90% diesel oil mixed with 10% of ethanol and emulsifiers. The emulsifiers can be such compounds as ethyl acetate, betz-dearborn, and biodiesels. These have the best stability with very little to no stratification. Performance and exhaust gas emissions of test engines were evaluated for single- and multi-cylinder, four stroke, and air and water cooled engines at various engine speeds and loads. The results showed that there was the increase in fuel consumption and brake specific fuel consumption (BSFC) since DE oil has less heating value than diesel oil. HC emissions were higher because of the amount of ethanol mixed in diesel oil and the injection timing needed to be advanced. CO and smoke emissions were lower due to better combustion that reduced these emissions [2]. However, thermal efficiency using DE oil was different depending on the emulsifier used. Alternatively, Huang et al. [6] investigated the performance and emissions of a single cylinder air cooled diesel engine at a constant speed and under various loads. The use of diesel oil mixed with ethanol and emulsified butanol (DEB oil) with diesel oil was compared. The results showed that DEB oil had similar fuel properties to diesel oil but a higher thermal efficiency. The BSFC was higher and emissions (CO and smoke) were lower, as was previously reported by Kumar et al. [2].

Another renewable fuel, syngas fuel, is currently used in diesel engines. Syngas, or synthesis gas, is a gas fuel mixture consisting primarily of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and methane (CH_4). It is produced from biomass by gasification. Unfortunately,

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doi: 10.14456/easr.2019.4

syngas has a high self-ignition temperature (typically above 500 °C). As a result, it cannot be ignited in a compression ignition diesel engine. Hagos et al. [7] discussed a possible way of utilizing syngas in diesel engines using a dual fuel, where diesel oil was injected as a pilot fuel to initiate the ignition, while syngas was introduced through the intake manifold of the engine using a mixing box or a carburetor. Since this technique is simple and reduces the quantity of tar, it did not damage the internal components of these engines. Many studies using diesel oil and synthesis gas as a dual fuel have been carried out. Some researchers [8-13] investigated the performance and emissions characteristics of diesel engines using various engine speeds and loads. Syngas was generated from gasified biomass (such as charcoal, sugarcane bagasse, and carpentry waste, wood pellets, waste wood chips, jatropha seeds, and press cake). The results showed that there were the increases in thermal efficiency and emissions (such as CO, HC, and black smoke), as well as decreased energy consumption. While Sutheerasak et al. [9] compressed 125 lpm of syngas combined with diesel oil as a dual fuel for comparison with diesel oil only, the maximum diesel saving was 41%, and thermal efficiency increased to 9.31% in agreement with other researchers [12-13]. Singh and Mohapatra [10] used syngas at a flow rate of 83 lpm achieving a maximum reduction in diesel consumption of 45.7%.

Other researchers [14-20] studied the use of various oils, esters and vegetable oils, combined with syngas that was not supercharged, in a dual fuel, comparing these oils with the use of diesel oil alone. The results showed that the emission levels of HC, CO, and smoke were lower, brake specific energy consumption (BSEC) was improved, and pilot fuel saving was increased by about 30%. However, these oils had a higher pour point and fuel viscosity than diesel oil, leading to a reduction in engine performance. Moreover, ester production was complex. Alternatively, DE oil had a lower fuel viscosity than esters with similar fuel properties as diesel oil depending on the emulsifiers used. DEB oil particularly gave better engine performance and lower emissions than diesel oil [2, 6]. Furthermore, there is a little research to investigate syngas and DEB oil use as a dual fuel. The objective of the current study is to investigate the performance and emission characteristics of a DI diesel engine using DEB oil and a dual fuel comprised of DEB oil combined with compressed synthesis gas.

2. Materials and methods

2.1 Syngas as a potential fuel for diesel engines

Syngas was generated from a gasifier system using charcoal ignited within a small downdraft system (1). A schematic and specifications of this gasifier are shown in Figure 1 and Table 1, respectively. The production of syngas as well as performance and emissions testing of a DI diesel engine using DEB oil and supercharged syngas as a dual fuel was done at the Automotive Biofuels and Combustion Engineering Research Laboratory, Mechanical Engineering Department, Faculty of Engineering, Burapha University.

First, about 10-15 kg of charcoal was weighed and fed into the top of a small downdraft gasifier (1). Air was introduced through the side of this gasifier using a blower. This increased the temperature and accelerated the gasification process. The gasification temperature ($T_{Gasification}$) was measured (18). Next, charcoal was reacted to form hot syngas, and it was sent to a cyclone (2) to trap solid particles. Then, the syngas flammability was tested using a flare (3), located between the cyclone (2) and wet scrubber (6).

Table 1 Gasifier specifications

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

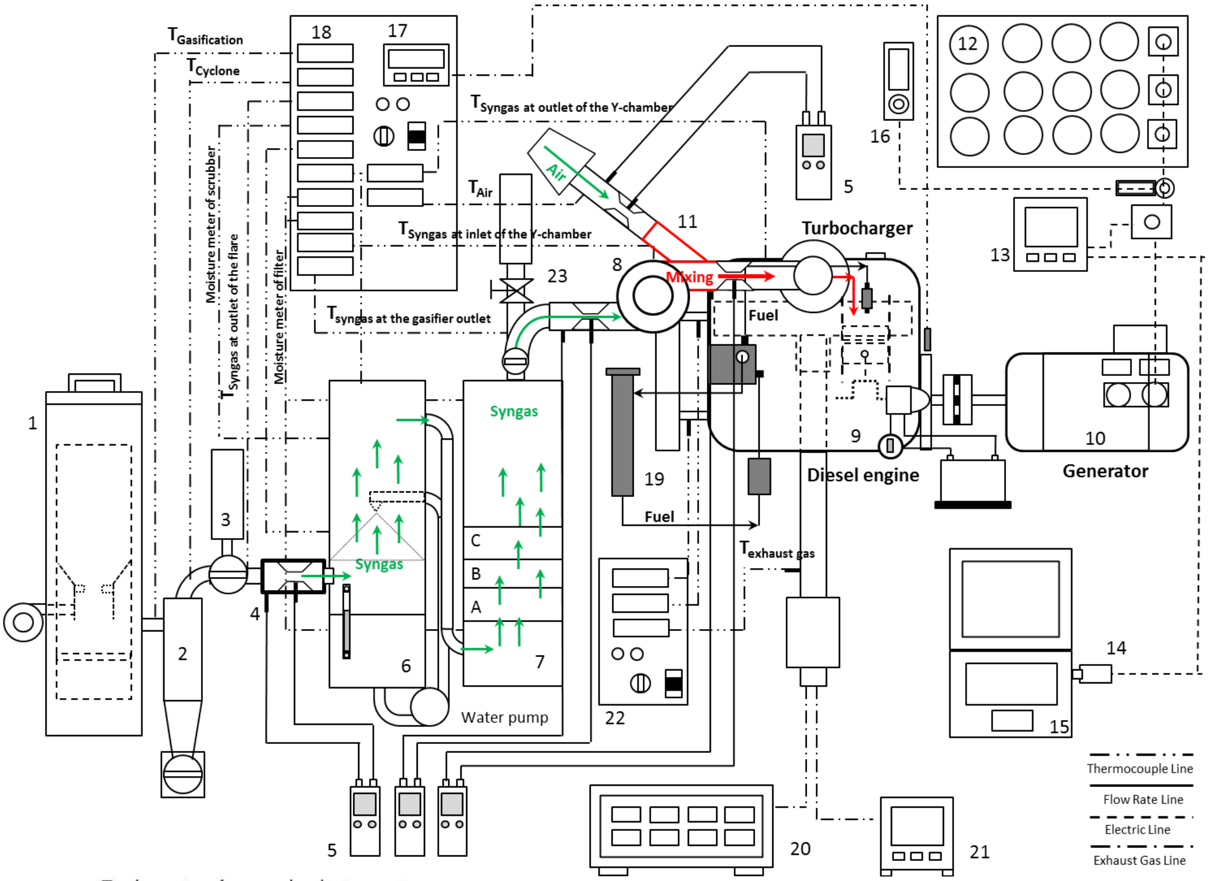
After the gas had burned for about 10 min, a valve at the flare (3) was closed to send the gas to a wet scrubber (6). Water was sprayed from the top mixing with the syngas to decrease its temperature and quantity of tar. This scrubber setup was used by Pathak et al. [21] in an investigation that measured the temperature and moisture of syngas using various meters (18). The cooled gas exiting this scrubber had various humidity levels. The gas then entered a sanded filter (7) to clean it and reduce its moisture content. The filters used in this research consisted of sawdust (A), coarse sand (B) and fine sand (C), respectively [21].

After this gas was cleaned, its flammability was checked using a flare (23) installed on the side of the sanded filter (7). After this gas had burned for 15 min, the flame was extinguished by closing the flare valve (23). Then, syngas samples were taken for gas chromatography analysis. The results shown in Table 2 were used to determine the caloric content of the syngas.

Finally, a blower (8) was used to compress the gas into a Y-shaped mixing chamber (11) where a turbocharger forced it into an intake manifold of the engine (9). This research used a Venturi tube (4) connected to a digital manometer (5), (DT-8890A, differential pressure manometer, CEM Instruments) to measure gas flow rates (syngas, air, and mixed gases).

Table 2 Syngas properties

Properties	Volume percent
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
Caloric value (MJ/m^3)	5.08±0.48



Equipment and measuring instruments:

1. Downdraft gasifier	2. Cyclone	3. Flare and valve	4. Venturi tube
5. Digital manometer	6. Wet scrubber	7. Sandbed filter	8. Blower
9. Diesel engine	10. AC generator	11. Mixing chamber	12. Electrical Load
13. Power meter	14. Hardlock	15. Computer	16. Clamp meter
17. Speed meter	18. Temperature meter	19. Fuel cylinder	20. Exhaust gas analyzer
21. Smoke meter	22. Engine temperature meter	23. Flare and valve of sandbed filter	

Figure 1 Schematic of the experimental setup

Table 3 Fuel properties

Properties	Viscosity @ 40 °C (mm^2/sec)	Density @ 15 °C (kg/m^3)	Flash point (°C)	LHV (MJ/kg)
ASTM	**D445**	**D1298**	**D93**	**D240**
Standard diesel oil [22]	1.80-4.10	810-870	52 (min)	-
Diesel oil	2.90	821	45	44.36
DEB oil	2.27	814	13	42.03
Anhydrous ethanol	1.40	794	14	26.70
Normal butanol	2.33	810	34	33.08

2.2 Preparation of DEB oil

DEB oil was synthesized via an emulsion process at the Biofuel and Alternative Fuel Laboratory, Chemical Engineering Department, Faculty of Engineering, Burapha University. The reactants used the diesel oil were anhydrous ethanol (a clear, colorless and homogeneous liquid, free of suspended matter, at least 99.9% ethanol by volume at 15 °C) and normal butanol (a chemical emulsifier). The ratio of diesel oil: ethanol: butanol used by other researchers [3-6] was to produce DEB oil was 90:5:5%vol. This ratio has the best stability with little-to-no stratification and properties to similar diesel oil. Next, the fuel properties were examined using various ASTM procedures. The kinematic viscosity, fuel density, flash point, and lower heating value (LHV) were determined and are shown in Table 3.

The properties of DEB oil compared to diesel oil show that its kinematic viscosity was reduced by 21.72%, fuel density decreased by 0.85%, flash point reduced by 32 °C, and its lower heating value decreased by 5.25%. Consistent with Huang et al. [6], the physical properties of anhydrous ethanol and normal butanol are generally have lower values than diesel oil, resulting lower values for the physical properties of DEB oil. The characteristics and qualities of standard diesel oil were published by the Department of Energy Business in 2013 [22]. This report indicates that DEB oil has a kinematic viscosity and fuel density within the prescribed range and can be used as a replacement fuel in future diesel engines.

2.3 Experimental setup of the diesel-engine generator test

Experiments were done using a four-stroke three cylinder direct injection diesel engine (9) [John Deere 3029DF150; 2.9 L; 43 kW (max) @ 2,500 rpm; compression ratio, 17.2.1 with a turbocharger]. A 20 kWe AC generator (10) was used to measure the output power. It was directly coupled to this engine with electric lamps to increase the electrical load (12). Output power varied depending on the electrical load. It was analyzed using a Richtmass RP-96EN power meter (13) through an IMARI-CT100/1A clamp, transmitting the signal via an RS485 to USB data converter and hard lock (14) connected to a computer (15). Additionally, the power meter parameters were calibrated by comparing them with those of a clamp-on meter. A fuel cylinder (19) was used to determine the flow rate of oils to calculate the fuel consumption.

System temperatures were monitored using K-type thermocouples connected to temperature meters in a control box (18, 22). Coolant, intake, exhaust gas, and gasifier system temperatures were recorded. The concentrations of exhaust gas emissions, CO_2, CO, and HC, were measured using a MOTORSCAN: 8020 eurogas emission analyzer (20) employing an IR Bench (infrared) method. Black smoke was measured with a MOTORSCAN: 9010 opacity meter/smoke detector (21). Specifications of the exhaust gas analyzer are shown in Table 4.

2.4 Experimental procedure

First, the engine was warmed up for about 15-20 minutes. Room temperature was 33±2 ^{o}C. After engine operation was stable, experiments were conducted using diesel oil and then DEB oil. In testing, engine speed was initially 1,000±50 rpm at full load and then the speed was increased to 1200±50 and later 1,600±50 rpm. The amount of fuel used in each experimental trial was 20 ml to investigate its consumption. Finally, parameters, such as air flow rate, electrical power, temperatures, and emissions, were recorded for comparison of the various fuel types.

Table 4 Specifications of the 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%

After completion of engine performance testing with diesel and DEB oils, supercharged syngas and DEB oil as dual fuel were used. First, syngas from the gasifier system was compressed by a blower (8) at 76 lpm and mixed with air in a mixing chamber (11). Then, the mixture was sent to a turbocharger, intake manifold and combustion chamber of this engine where the DEB oil was separately injected using standard injection timing. The engine performance test conditions, as well as the recorded parameters, were the same as for the tests using diesel and DEB oils. The syngas flow rates used in this study were 76, 79, 85, 93, 103, 116, and 125 lpm and the length of the engine tests were between 50 and 100 hours [9].

2.5 Performance characteristics analysis

The power output was taken as the electrical power generated. Engine performance [9] was determined from the mean effective pressure, electrical efficiency, specific energy consumption, and fuel consumption rate. The engine performance was calculated as follows:

$$\mathrm{MEP} = \frac{60\mathrm{P_{ele}} \,.\, \mathrm{n_r}}{\mathrm{V_d} \,.\, \mathrm{N}} \quad (1)$$

$$\eta_{\mathrm{ele}} = \frac{\mathrm{P_{ele}}}{\dot{m}_f\,\mathrm{LHV_f} + \dot{m}_{SG}\,\mathrm{LHV_{SG}} + \mathrm{P_{Blower}}\eta_{\mathrm{Blower}}} \times 100 \quad (2)$$

$$\eta_{\mathrm{Blower}} = \frac{\dot{V}_{SG}\Delta p_t}{102\mathrm{P_{Blower}}} \times 100 \quad (3)$$

$$\mathrm{SEC} = \frac{\dot{m}_f \,.\, \mathrm{LHV_f} + m_{SG}\,\mathrm{LHV_{SG}} + \mathrm{P_{Blower}}\,\eta_{\mathrm{Blower}}}{\mathrm{P_{ele}}} \quad (4)$$

$$\mathrm{FCR} = \rho_f\left(\frac{3600\mathrm{V_f}}{t}\right) \quad (5)$$

Where:

MEP	: Mean effective pressure (bar)
η_{ele}	: Electrical efficiency (%)
η_{Blower}	: Blower efficiency (%)
SEC	: Specific energy consumption (MJ/kW$_e$.h)
FCR	: Fuel consumption rate (kg/hr)
P_{ele}	: Electrical power (kW$_e$)
P_{Blower}	: Blower power (kW$_e$)
$\dot{m}_f$	: Mass flow rate of fuel (kg/sec)
$\dot{m}_{SG}$	: Mass flow rate of syngas (kg/sec)
$\dot{V}_{SG}$	: Volume flow rate of syngas (m^3/sec)
V_f	: Volume of fuel in testing (m^3)
ρ_f	: Fuel density (kg/m^3)
t	: Time using fuel (sec)
Δp_t	: Total differential pressure (mm$_{WC}$)
LHV_f	: Lower heating value of diesel fuel (MJ/kg)
LHV_{SG}	: Lower heating value of syngas (MJ/kg)
n_r	: Number of revolutions per power stroke (rev/cycle)
V_d	: Displacement volume (m^3)
N	: Engine speed (rpm)

3. Results and discussion

Performance and emissions tests were conducted using a diesel engine running on a dual fuel, i.e., DEB oil (DEB) as the primary fuel and syngas (SG) compressed at 76, 79, 85, 93, 103, 116 and 125 lpm as a secondary fuel. These fuels are designated as DEB+SG76 lpm, DEB+SG79 lpm, DEB+SG85 lpm, DEB+SG93 lpm, DEB+SG103 lpm, DEB+SG116 lpm, and DEB+SG125 lpm, respectively.

DEB oil and supercharged syngas as dual fuel was compared with DEB and diesel oils alone in terms of electrical efficiency, specific energy consumption, fuel consumption rate, and exhaust gas temperature at engine speeds from 1,000 to 1,600 rpm and full load in terms of MEP. The results are described below.

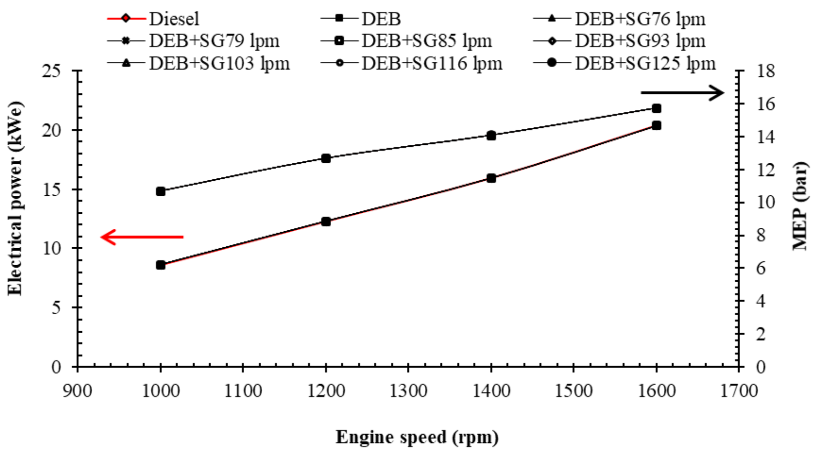


Figure 2 Electrical power and MEP at various engine speeds

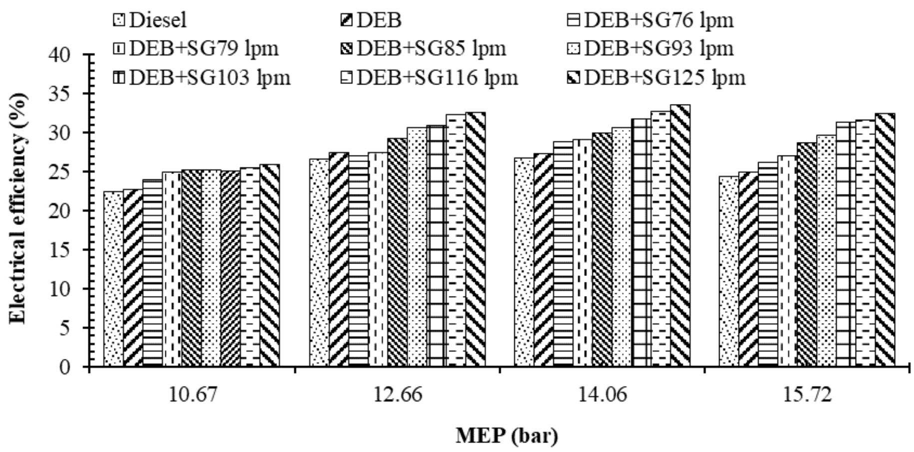


Figure 3 Electrical efficiency at various MEP

3.1 Electrical power

The current study examined the power output in the form of generated electrical power to calculate the MEP as shown in Figure 2. The electrical power and MEP increased with engine speed. When using a dual fuel, the DEB oil combined with increasing amounts syngas from 76 to 125 lpm, the electrical power and MEP were similar to using DEB and diesel oil. The specific engine speeds used in this study were 1,000, 1,200, 1,400 and 1,600 rpm, producing electrical power of 8.63±0.02, 12.29±0.02, 15.923±0.03, and 20.337±0.03 kW_e respectively, with MEP values of 10.67±0.003, 12.66±0.003, 14.06±0.002 and 15.72±0.002 bar, respectively.

3.2 Electrical efficiency

Electrical efficiency was calculated from the ratio between the highest electrical power output and the total energy input, as shown in Figure 3. This figure indicates that the electrical efficiency improved with additional syngas quantity and increased MEP. The maximum electrical efficiency occurred at a MEP of 14.06 bar. Using DEB oil resulted in increased electrical efficiency of 0.53% compared to diesel oil. This result is consistent with Huang et al. [6] since the fuel consumption rate for the DEB oil was lower than the corresponding decrease of the fuel heating value of this oil. Moreover, this oil had a higher oxygen (O_2) content that improved combustion, especially diffusion combustion, which contributed to higher electrical efficiency [1-3]. Therefore, this oil is suitable as an alternative fuel in the future while diesel oil will be less important due to limited resources. The electrical efficiency using DEB oil was 0.97% lower than previously reported [6].

Next, syngas was combined with DEB oil and used as dual fuel with increasing the syngas quantity from 79 to 125 lpm. Compared with DEB and diesel oils alone, electrical efficiency increased with increasing syngas quantity. At maximum efficiency using DEB and diesel oils alone, an increased quantity of syngas, from 79 to 125 lpm, increased the electrical efficiency from 1.83 to 6.24% and 2.15 to 6.77% respectively. This result is consistent with Das et al. [8]. Better combustion of a relatively rich syngas-air mixture resulted in a quick premix combustion phase and better combustion of the DEB oil and syngas mixture. This resulted in a reduced total energy input. Moreover, increasing the syngas quantity relatively decreased the DEB oil proportion, reducing the total energy input. These factors led to improved electrical efficiency [7-12, 23]. Additionally, it was found that using DEB oil and compressed syngas at 125 lpm (DEB+SG125 lpm) yielded the highest electrical efficiency.

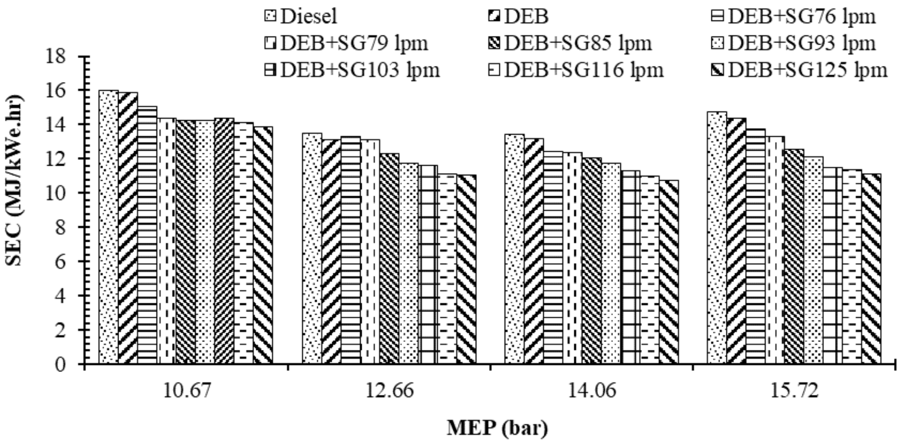


Figure 4 SEC with various MEP

Additionally, this research compared the use of DEB+SG125 lpm with Diesel+SG125 lpm from the research of Sutheerasak et al. [9] demonstrating a 2.06% lower electrical efficiency for the former. This can be explained by examining Eq. (2). Using diesel oil combined with an increased syngas quantity, 125 lpm, showed a fuel savings of up to 33.60% [9]. As a result, the energy input from diesel oil was significantly reduced. Hence, the total energy input using Diesel+SG125 lpm was lower than DEB+SG125 at the same power output. Therefore, the electrical efficiency using Diesel+SG125 lpm is higher than for DEB+SG125.

3.3 Specific energy consumption

The variation between specific energy consumption (SEC) at various gas flow rates and MEP is shown in Figure 4. The SEC was calculated from the ratio of the total energy input from the fuel consumption rate, the fuel's caloric value and the electrical power output at full load. The SEC using DEB oil was 1.93% lower compared to diesel oil at maximum efficiency. This result is consistent with previous research [2-3, 6]. The SEC was inversely proportional to the electrical efficiency. Additionally, it was observed that DEB oil has a smaller lower fuel heating value than diesel oil (Table 3) although the fuel consumption of this oil was a little higher.

Compressed syngas combined with DEB oil as a dual fuel resulted in a decreasing SEC with increasing syngas quantities. Compared with the use of DEB oil alone, DEB oil combined with an increasing amount of compressed syngas, from 76 to 125 lpm at maximum efficiency, the SEC decreased from 13.45 to 10.73 MJ/kW$_e$.hr, increasing the energy-savings from 5.62 to 18.62%. Compared with using diesel oil alone at maximum efficiency, DEB oil and supercharged syngas yielded increased energy-savings from 7.44 to 20.19%. The results of the current study are consistent with earlier work [8-9, 13]. Supercharged syngas reduced the proportion of DEB oil injected into the combustion chamber. Additionally, the increased density of the syngas-air mixture resulted in a more complete combustion.

Comparing the use of DEB+SG125 lpm with Diesel+SG125 lpm from [9] indicates that the SEC is higher than 6.13%. This can be seen in Eq. (4). Using Diesel+SG125 lpm decreased the proportion of diesel fuel injected into the combustion chamber, increasing the fuel savings by 33.60% [9]. Therefore, the total energy input from Diesel+SG125 lpm was lower than the total energy input from using DEB+SG125 lpm, whereas the power output was the same. Additionally, the SEC had the opposite effect on electrical efficiency. Using Diesel+SG125 lpm yielded higher electrical efficiency than DEB+SG125 lpm.

3.4 Fuel consumption rate

As can be seen in Figure 5, the fuel consumption rate (FCR) increased with increasing MEP. Comparing the use of DEB oil with diesel, the FCR increased by 3.51% at maximum efficiency. It can be concluded that using DEB oil requires more fuel than diesel oil, which is consistent with previous studies [1-6, 24]. Since the DEB oil has a smaller lower fuel heating value than diesel oil under the same conditions, more DEB oil is required than diesel oil.

Comparing the use DEB oil and compressed syngas as a dual fuel with DEB and diesel oils alone demonstrates that the FCR decreased with increasing syngas quantity. Use of supercharged syngas combined with DEB oil compared with DEB and diesel oils alone at maximum efficiency indicates that the FCR decreased from 8.14 to 22.47% and 4.92 to 19.75%, respectively. These results are consistent with previous studies [7-13].

The use of DEB oil combined with increasing syngas quantities yielded a more rapid start of ignition by opening the injector needle more quickly. This led to a reduction of the proportion of DEB oil consumed. Therefore, using DEB oil and compressed syngas as a dual is more fuel efficient than using DEB or diesel oils alone. Additionally, the current study found that the most fuel-savings occurred when using DEB+SG125 lpm at 15.72 bar of MEP. The fuel savings increased by 25.85% and 23.53% compared with the use of DEB and diesel oils, respectively.

This result is compared with Sutheerasak et al. [9] demonstrating that the use of compressed syngas and DEB oil has less fuel savings than using diesel oil and supercharged syngas as a dual fuel. It was 15.15% lower [9] and 19.85% lower [10] than earlier studies. Diesel oil was injected with a normal timing while diesel oil combined with increasing syngas quantities reduced the proportion of diesel oil needed [8-9]. It is also important to consider that DEB oil has a lower fuel viscosity and density than diesel oil, so these properties affected the fuel injection mechanism, negatively impacting fuel injection timing. While this oil was combined with syngas in a dual fuel, it caused the injector needle to open and close quickly, allowing an increased fuel flow rate. However, DEB oil has a smaller lower heating value than diesel oil. As a result, the frequency of diesel fuel injection

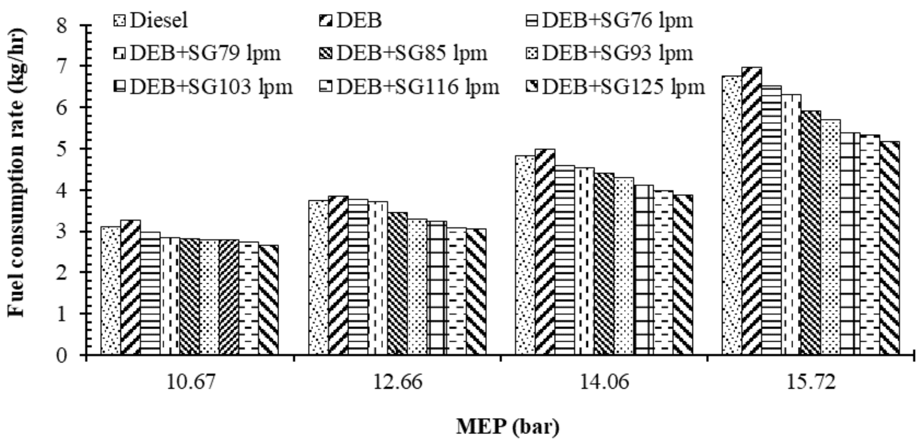


Figure 5 Fuel consumption rate at various MEP values

Table 5 Comparison of fuel production costs

Fuel		Prices	CC (kg/hr)	FC (lit/hr)	TEI (kW)	P_{ele} (kW_e)	FPC (Bath/kW.hr)
Diesel oil		29.59[a]	-	8.23	83.22	20.334	11.97
DEB oil		38.63[a]	-	8.56	81.32	20.336	16.25
DEB+SG	DEB	38.63[a]	-	6.35	62.39	20.340	14.51
	Charcoal	10[b]	5	-			

Note: [a] baht/litre and [b] baht/kg

needed to increase to produce the same power output as diesel oil combined with compressed syngas. The quantity of pilot DEB oil was higher than the amount of pilot diesel oil.

Comparison of fuel production costs (FPC) between diesel oil, DEB oil and DEB combined with syngas (DEB+SG) as a dual fuel [25], is shown in Table 5. The price of fuels was estimated from the general wholesale price and the cost of charcoal to produce syngas. At an engine speed of 1,600 rpm, the current study engine produced 20.337±0.03 kW_e of electrical power. The use of DEB+SG125 lpm resulted in a fuel saving of 25.85% compared to DEB oil alone. This indicates that DEB oil had 35.77% higher fuel production costs (FPC) than diesel oil. Alternatively, DEB+SG125 lpm had 10.71% lower fuel production costs (FPC) than DEB oil. When using DEB+SG125, the consumption of DEB oil was 6.35 litres/hr, combined with syngas produced from 5 kg/hr of charcoal. As a result, the total energy input (TEI) using DEB+SG125 lpm decreased by 23.28% compared with using DEB oil alone.

3.5 Exhaust gas temperature

The trends of exhaust gas temperature (EGT) with increasing gas flow rate and MEP are shown in Figure 6. When using DEB oil compared to diesel oil, the EGT from the former was lower. This result is consistent previous studies [1, 4-6]. DEB oil has a higher latent heat of evaporation due to the presence of an emulsifier. Combustion in the second phase was partially oxidized (OH radicals) and, hence, a decreased combustion temperature reduced exhaust gas temperatures.

Use of supercharged syngas and DEB oil as a dual fuel compared with DEB and diesel oils alone indicated that the EGT increased with increasing syngas quantity and MEP. Compressed syngas and DEB oil as a dual fuel compared with DEB and diesel oils alone at maximum efficiency yielded increased EGT by 25 to 55 ^oC and 17 to 47 ^oC respectively. These results are similar to previous studies [8-14] where syngas contained CO_2 and CO (Table 2). It exhibited changed combustion phenomena in the diffusion combustion phase, which led to a longer late combustion period. It burned continuously until the exhaust valve was opened.

While the use of DEB+SG125 lpm compared with Diesel+SG125 lpm from Sutheerasak et al. [9] and Shrivastava et al. [22] showed that using DEB+SG125 lpm reduced exhaust gas temperatures, the temperature drop was 24 ^oC and 125 ^oC, respectively. DEB oil contained more carbon, hydrogen, and oxygen (C-H-O) molecules that with syngas as a dual fuel, led to better combustion, and therefore, a reduction of the late combustion period [14-20].

3.6 Carbon dioxide

Since the release of carbon dioxide (CO_2) greatly affects global warming and the greenhouse effect, it is necessary to measure the CO_2 emissions from this engine. As indicated in Figure 7, the release of CO_2 increased with the MEP. Comparing the CO_2 emissions using DEB oil and diesel oil, the CO_2 emission from combustion of the former decreased by 1.15%vol at maximum efficiency. This is consistent with Huang et al. [6], who found that the C/H ratio of this oil altered CO_2 formation due to the presence of O_2 molecules. As a result, there were fewer carbon molecules per volume compared to diesel oil. Moreover, the lower exhaust gas temperatures implied that the lower burning temperature was due to the higher latent heat of vaporization of DEB oil [1-2].

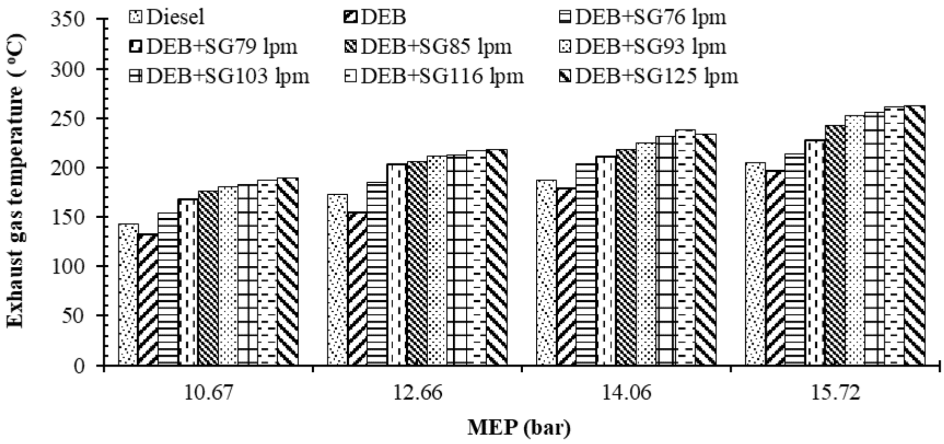


Figure 6 Exhaust gas temperatures at various MEP levels

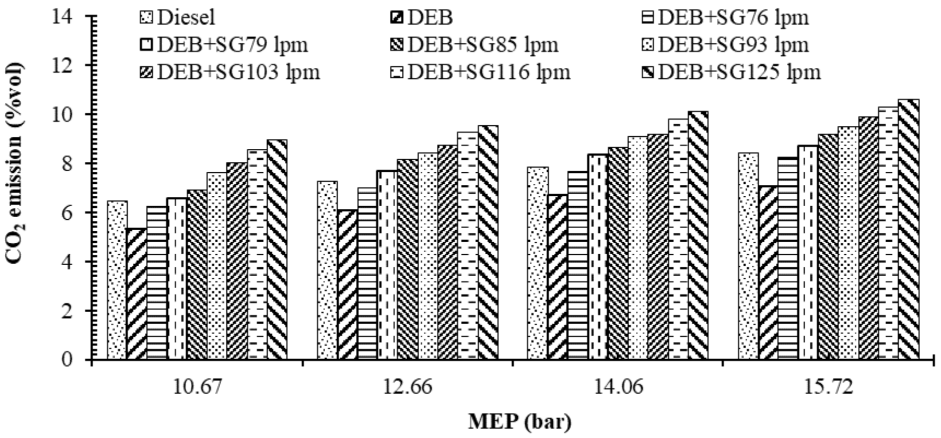


Figure 7 Carbon dioxide levels at various MEP levels

Combustion of compressed syngas combined with DEB oil compared with DEB and diesel oils alone shows that there is a different type of change in CO_2 formation than when using just DEB oil. The release of CO_2 from the combustion of DEB oil and supercharged syngas as a dual fuel increased with increasing syngas quantity and MEP. Use of compressed syngas and DEB oil as a dual fuel compared with DEB and diesel oils only at maximum efficiency demonstrates that the CO_2 emission increased from 0.95 to 3.43%vol, and 0.49 to 2.27%vol, respectively. The results of the current research are consistent with previously published reports [9, 12, 15, 23] because syngas contains both CO and CO_2 (Table 2). As the oxygen content of the fuel decreased, there was an increase in combustion temperature and a steep rise in the release of CO_2.

Comparing the combustion of DEB+SG125 lpm with Diesel+SG125 lpm from Sutheerasak et al. [9] showed that DEB+SG125 lpm produces lower carbon dioxide emissions, decreased by 0.86%vol. DEB oil combined with syngas as dual fuel can lead to a more complete combustion than that of diesel oil or syngas alone. Moreover, DEB oil has a lower C/H ratio than diesel oil [1-2] which helps in reducing the late combustion period and its temperature. These both result in lower CO_2 emissions [14-20]. However, Rith et al. [12] found that carbon dioxide emissions increased by 4.12%vol. This is because the quantity of syngas used in the current study was greater.

3.7 Carbon monoxide

The trends in the carbon monoxide (CO) emissions are shown in Figure 8. It is evident from the figure that the amount of CO decreased with increasing MEP. Using DEB oil with this engine reduce CO emissions by 0.04% by volume compared to diesel oil at maximum efficiency. This is consistent with Huang et al. [6]. Such CO reductions were due to a more complete combustion as the ethanol-butanol blend had a higher O_2 content than diesel oil [24].

However, Figure 8 shows that increasing the quantity of syngas combined with DEB oil as a dual fuel yields a higher level of CO emissions compared with using DEB and diesel oils alone. At maximum efficiency, there was an increase in CO emissions, from 0.12 to 0.49%vol, and 0.08 to 0.44%vol, respectively. These results are consistent with those of other researchers [9-12, 22]. Although syngas has a much wider ignition range than diesel fuel, it can be burned leaner than diesel oil, reducing CO emissions [26]. This might have been due to the presence of CO in the syngas, which is in the highest quantity (Table 2), excluding N_2. The more syngas that was flowed to the intake manifold, the less of air flow to the engine, as well as the amount of O_2 required for complete combustion [27]. The presence of CO in the syngas in duel fuel operations resulted in significant increases in the CO emissions compare using DEB and diesel oils alone. Overall emissions of CO for all DEB+SG increased with the amount of syngas used.

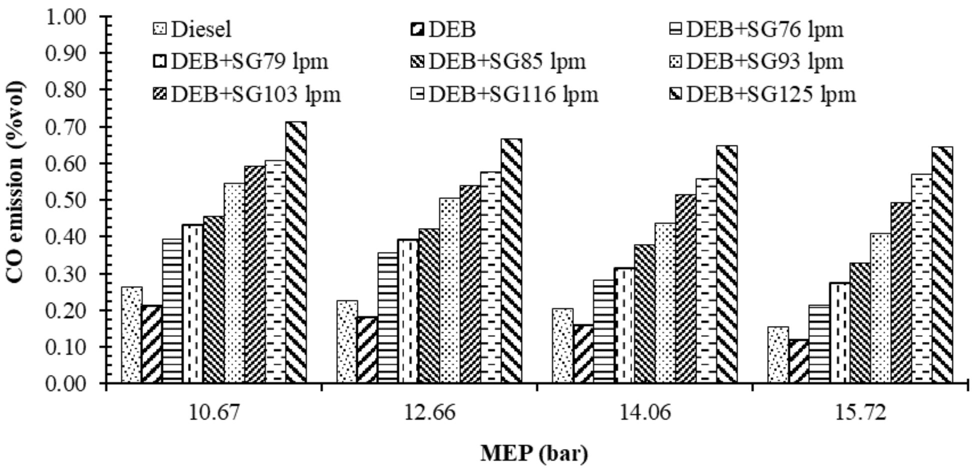


Figure 8 Carbon monoxide levels at various MEP

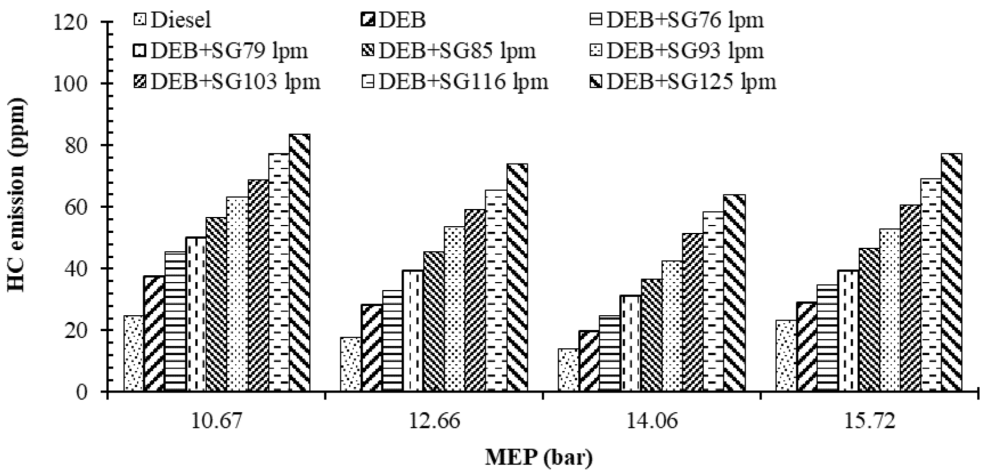


Figure 9 Hydrocarbon levels at various MEP

Comparing CO emissions from the use of DEB+SG125 lpm and Diesel+SG125 lpm from Sutheerasak et al. [9], using the former produced 0.193%vol lower CO emissions. DEB oil consists of C-H-O molecules and the extra O_2 molecules enhance combustion consuming more C molecules. This reaction, then, reduces CO emissions to a higher degree than the use of diesel oil and syngas as a dual fuel [14-20].

3.8 Hydrocarbons

The emission of hydrocarbons (HC) with varying MEP when using the dual fuel and only DEB or diesel oils are presented in Figure 9. An increase of 5.85 ppm of HC emissions at the maximum MEP resulted from the use of DEB instead of diesel fuel, following the same trend as in an earlier study [1] that hypothesized that the higher heat of evaporation of the ethanol-butanol blend that increases HC emissions. Such increased HC emissions, creates an undesirable unburned zone [6] during fuel injection into the cylinder. The spray penetration changes causing unwanted fuel impingement on some areas of the cylinder wall and piston rings.

This figure also shows the trends of HC emissions from the use of supercharged syngas combined with DEB oil. It was found that HC emissions increased with the syngas quantity. Compressing syngas and DEB oil as a dual fuel compared with the use DEB and diesel oils alone at maximum efficiency shows that the HC emission increased from 4.19 to 44.19 ppm and 10.76 to 50.04 ppm, respectively. This is consistent with the results previous studies [9-12]. The increased HC emissions is a direct result of incomplete combustion. The high syngas content combined with DEB oil injection will result in less O_2 in the fuel mixture. Therefore, the greater a deficiency of O_2 will increase CO and HC emissions. Less O_2 is available for combustion with increasing syngas quantities, resulting in high CO_2 emissions and some water (H_2O). At the same time, there were not enough O_2 molecules to completely react with the available C and H molecules, leading to incomplete combustion. CO_2 production was reduced resulting in the formation of undesirable combustion products, especially HC and CO.

In Figure 9, the emission of HC when using DEB+SG125 lpm was 35.15 ppm higher than for Diesel+SG125 lpm [9]. Such higher HC emissions were due to the higher heat of evaporation of the DEB. Therefore, more unburned hydrocarbon was produced than from diesel oil [1]. With increasing syngas content, the degree of incomplete combustion and HC emissions increases [14-20].

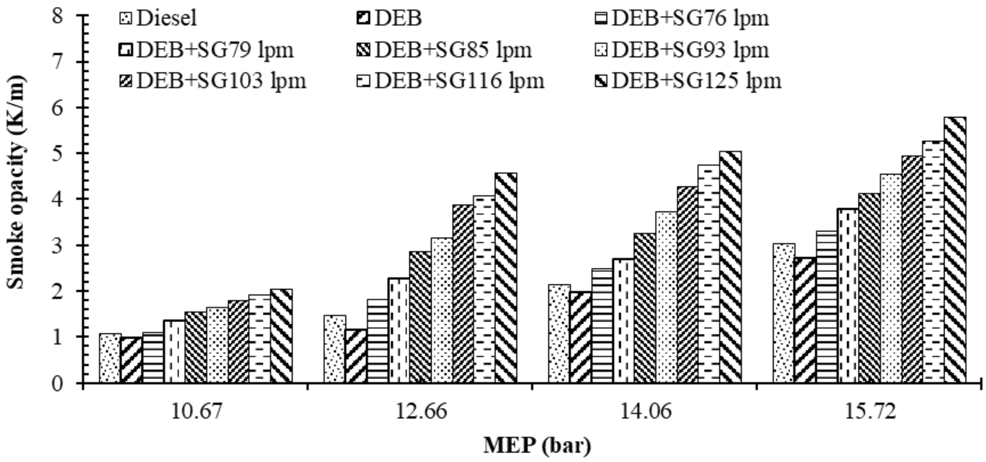


Figure 10 Smoke levels at various MEP

3.9 Black smoke

Black smoke is comprised of particulate matter that results from incomplete combustion of hydrocarbons. The current research investigates black-smoke release indicated by smoke opacity as shown in Figure 10. Black-smoke release trends increase with MEP. Combustion of DEB oil resulted in a 0.18 K/m lower smoke opacity than diesel oil. This result is consistent with the research work of Huang et al. [6] and it arises because of the O_2 content in an ethanol-butanol blend enhances combustion during the diffusion combustion phase, which subsequently reduces smoke opacity.

Smoke opacity increased as the quantity of syngas combined with DEB oil was increased and with the MEP. Figure 10 shows that using DEB oil and compressed syngas as a dual fuel leads produces higher levels of black-smoke. These results are consistent with those of other researchers [7-14]. This phenomenon arises due to the greater amount of C molecules as the syngas content is increase while the O_2 content is decreased as the amount of air is concurrently reduced during injection. The level of smoke opacity is directly correlated with the level of CO and HC emissions.

This result is compared with Sutheerasak et al. [9]. Combustion of DEB+SG125 lpm produces less black-smoke than Diesel+SG125 lpm, with 0.09 K/m lower opacity levels. DEB oil has a higher O_2 content that improves combustion. It produces a more complete combustion than diesel oil or syngas as a dual fuel [14-20].

4. Conclusions

The performance and exhaust emission characteristics of a diesel-engine burning diesel oil, DEB oil, and a duel fuel consisting of DEB oil with several levels of compressed syngas was studied. The findings are as follows.

1) With a little higher consumption, combustion of DEB oil is more efficient with a lower SEC than diesel oil. It also has a lower exhaust gas temperature, CO_2 and CO emissions, and less black-smoke due to its higher O_2 content. However, HC emissions are increased due to the higher heat of evaporation of the ethanol-butanol blend.

2) Engine performance from combustion of supercharged syngas combined with DEB oil is higher than using DEB or diesel oils alone. Combustion of compressed syngas in a dual fuel increases the efficiency and reduces the SEC. As the syngas quantity is increased, fuel savings are increased due to a faster auto-ignition.

3) The exhaust gas temperature and emissions from the combustion of a dual fuel (DEB and compressed syngas) show several disadvantages. The additional C and O_2 content increases the exhaust gas temperature and greatly increases CO_2 emissions. As the flow of compressed syngas increases, the level of O_2 in the air/fuel mixture is decreased. Hence, greater amounts of pollutants, such as CO, HC, and black smoke, are released due to incomplete combustion.

5. Acknowledgements

The authors acknowledge financial support (Grant No. 9/2552) from the Faculty of Engineering, Burapha University, Thailand. Additionally, the authors thank Mr. Chatree Lerdphukaew, Mr. Naratip Panlai and Mr. Witthawat Ruxsasin for their help in data collection.

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