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Original Article

Comparison of using DEE oil with supercharging syngas and DEE oil on dual fuel in a turbocharging diesel engine

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Abstract

Developing renewable fuels, especially diesel mixed to ethanol and ethyl acetate (DEE) and syngas, for applying in diesel engines are interesting nowadays. The article is to study the performance and emissions of a turbocharging diesel engine, which was four-stroke, three-cylinder, and direct-injection system, by using the DEE compared with dual fuel between syngas compressed from 76 to 125 lpm and this oil. Results of engine test to speed from 1,000 to 1,600 rpm at full load from using DEE indicated that engine performance was slightly reduced, but there was the decrease of more emissions to compare with diesel. On the other hand, using DEE and supercharging syngas on dual fuel gave higher engine performance than using DEE only. Compressing syngas at 125 lpm combined to DEE was found that fuel saving increased to 26.40%, but various emissions were enormously increased with increasing syngas flow rate.

Keywords: DEE, supercharging syngas, engine performance, emissions

1. Introduction

Currently, diesel engines are applied in the agriculture sector because of higher efficiency and lower maintenance costs. However, the problem of diesel prices and various emissions, especially carbon monoxide (CO), hydrocarbons (HC) and black smoke, leads to developing alternative fuels, particularly ethanol and syngas, (Sutheerasak, Pirompugd, & Sanitjai, 2018).

Kumar, Cho, Park, and Moon (2013) explained that the use of diesel blended with ethanol (DE) was the best choice because of the non-modified engine and more complete combustion. DE to produce from the 90% of diesel mixed with 10% of ethanol and ethyl acetate by the emulsion method had the best stability with minimal and almost unseen stratification since ethyl acetate was easily emulsifier which produced from the esterification of ethanol and low cost. Sutheerasak (2017) investigated the fuel properties and engine performance from using the 90% of diesel blended with 5% of ethanol and 5% of ethyl acetate (DEE) compared with diesel. Properties of DEE were similar to diesel, but the engine showed higher fuel consumption, while the exhaust gas possesses less CO and smoke.

Syngas, which consisted primarily of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and methane (CH_4), was produced from biomasses by using various gasifiers. However, syngas had a high self-ignition temperature, and it could not be ignited by compression ignition in a diesel engine. Yaliwal, Banapurmath, and Revenakar (2016) explained that the use of syngas and diesel in dual fuel mode was a better way because of non-complex method and non-modified engine. For investigating dual fuel between diesel and syngas, Lal and Mohapatra (2017) and Singh and Moha patra (2018) generated syngas from biomasses, such as sawdust, cotton stalks, sugarcane bagasse, etc. Sutheerasak *et al.* (2018) used charcoal to produce syngas because of lower humidity than these biomasses. Results of engine test showed

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that there was the change of engine performance and diesel injection was decreased about 60%, but there was the increase of CO, HC, and black smoke as increasing the gas flow rate. To reduce these emissions, Hemanth, Prashanth, Benerjee, Choudhuri, and Mrityunjay (2017), Nayak and Mishra (2017), and Hadkar and Amarnath (2015) generated syngas to combine with esters on dual fuel. The result showed that the levels of HC, CO, and black smoke were lower, brake specific energy consumption was improved, and fuel replacement was increased by about 35%.

However, esters had a higher fuel viscosity than diesel led to the reduction of engine performance. Moreover, esters were synthesized by a complicated method. On the other hand, DE was lower fuel viscosity than esters, and it was similar fuel properties to diesel depending on the emulsifiers (Kumar *et al.*, 2013). Furthermore, there is little research to investigate the use of syngas and DEE on dual fuel. The article is to present the investigating performance and emissions of a turbocharging diesel engine from using DEE compared with dual fuel between DEE and increasing syngas flow rate from using the supercharger.

2. Materials and Methods

2.1 Preparation of syngas

Syngas was prepared from a downdraft gasifier by using charcoal as shown in Figure 1. Specifications of the gasifier are shown in Table 1. Charcoal was fed into the gasifier through the top while the air was entranced at the side by using a blower to generate the syngas. After syngas was produced from the gasifier, it was sent into a cyclone before it was entered to a wet scrubber and a filter tank to clean and reduce the moistness.

At the same time, syngas sample from the filter tank was taken to analyze the various components by using a gas chromatography while this gas had ingredients and calorific value which came from the calculation as shown in Table 2. Finally, it was sucked by the supercharger, which was a variable speed blower, to send into a Y-shape mixing box to blending with air, and absorbed by a turbocharger into an intake manifold of this engine. For measuring the flow rate of syngas and air, the flow conditioning was installed before the mixing box, and a venturi tube and a digital manometer were applied in this research.

Table 1. Gasifier specification.

Item	Description
Type of gasifier	Closed top downdraft
Maximum Capacity (kW_{th})	75
Rate charcoal 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

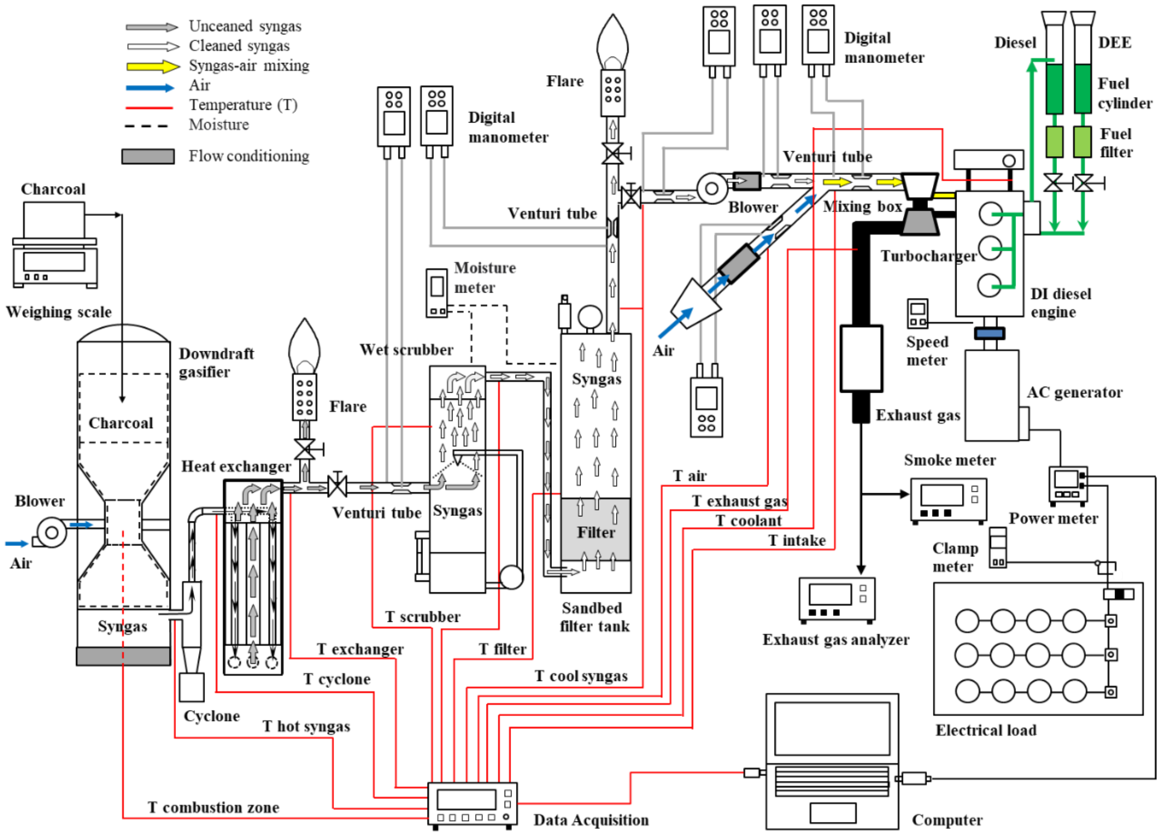

Figure 1. Schematics of the experimental setup.

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

2.2 Production of DEE

Reactants consist of diesel, anhydrous ethanol (99.9%w) and ethyl acetate (99.6%w) blended by the electromagnetic machine. The ratio of diesel: ethanol: ethyl acetate was 90:5:5 %vol as studied from Isarachewa (2006). Physical properties of DEE were compared to diesel by using ASTM standard, which consisted of flash point, pour point, kinematic viscosity, fuel density, and lower heating value (LHV) shown in Table 3. Flash point decreased to 32 ºC, pour point increased to 2 ºC, density decreased to 1.22%, viscosity decreased to 22.41%, and LHV decreased to 7.26% respectively.

The cause of physical properties of DEE was inferior to diesel, because physical properties of ethanol and ethyl acetate were lower than diesel as consistent with Isarachewa (2006) and Sutheerasak and Chinwanitcharoen (2016). However, DEE could be applied as an alternative fuel with the diesel engines in the future because some properties, particularly viscosity and density, were within the scope of standard diesel determined by the Department of Energy Business (Sutheerasak & Chinwanitcharoen, 2016).

2.3 Experimental setup

Experiments were carried out on a three-cylinder direct injection diesel engine connected with turbocharger system, Model, John Deere 3029DF150; capacity, 2.9 L; power (max.), 43 kW @ 2,500 rpm; compression ratio, 17.2.1. A 20 kW_e AC generator was applied in this experiment as directly coupled to this engine by using electric lamps to increase the electrical load (Figure 1). The output power was shown in the term of electrical power measured from a power meter of richtmass RP-96EN by connecting with a computer. For investigating the engine speed and the flow rate of diesel and DEE to calculate the fuel consumption, this research used a speed meter and a fuel cylinder. For measuring the fluid temperatures, such as coolant, intake, exhaust gas, etc., the K-type thermocouple was applied with data acquisition. Final, exhaust gas emissions, such as CO_2, CO, and HC, were investigated from the MOTORSCAN: 8020 eurogas emission analyzer and the MOTORSCAN: 9010 smoke detector to measure the smoke opacity as referred from Sutheerasak, Pirompugd, Ruengphrathuengsuka, and Sanitjai (2019).

2.4 Experimental procedure

The engine was firstly warmed up about 15 min, while the ambient temperature was at 33±2 ºC. After engine operation was stable, experiments were started up by using diesel, DEE, and dual fuel between DEE and increasing syngas flow rate (DEE+SG) compressed by the blower, respectively. 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 DEE). The flow rate of air entering the mixing box was controlled at 76 lpm because increasing syngas resulting engine stopped. The syngas flow rate was studied at 76, 79, 85, 93, 103, 116, and 125 lpm, and terms were shown as DEE+SG76, DEE+SG79, DEE+SG85, DEE+SG93, DEE+SG103, DEE+SG116, and DEE+SG125 lpm.

2.5 Performance analysis

Engine performance analysis in this research studied from Sutheerasak *et al.* (2019) as shown below.

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

$$\eta_{ele} = \frac{P_{ele}}{\dot{m}_f\, LHV_f + \dot{m}_{SG}\, LHV_{SG} + P_{Blower}\eta_{Blower}} x100 \quad (2)$$

$$\eta_{Blower} = \frac{\dot{V}_{SG}\, \Delta p_t}{102P_{Blower}} x100 \quad (3)$$

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

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

Where

MEP : Mean effective pressure (bar)
η_{ele} : Electrical efficiency (%)
η_{Blower} : Blower efficiency (%)
SEC : Specific energy consumption ($MJ/kW_e.hr$)

Table 3. Fuel properties.

Items	Flash point (ºC)	Pour point (ºC)	Density @ 15 ºC (kg/m^3)	Viscosity @ 40 ºC (mm^2/sec)	LHV (MJ/kg)
ASTM	D93	D97	D1298	D445	D240
Diesel	45	1.5	821	2.90	44.36
DEE	13	3.5	811	2.25	41.14
Ethanol	14	-83.5	794	1.40	26.70
Ethyl acetate	-5	-	903	-	23.15

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 of using fuel (sec)
Δp_t : Total differential pressure (mm_{WC})
LHV_f : Low heating value of diesel fuel (MJ/kg)
LHV_{SG} : Low 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

Before investigating performance and emissions characteristics, this research calculates the MEP because it is a quantity relating to the engine parameters and a valuable measure depended on power and speed. This research controlled the equal speed and power to study the change of both characteristics as referred from Sutheerasak *et al.* (2019). All speed used in this study were at 1,000, 1,200, 1,400 and 1,600 rpm. Electrical power from these speeds equaled 8.63±0.02, 12.29±0.02, 15.923±0.03, and 20.337±0.03 kW_e respectively, and MEP equaled 10.67±0.003, 12.66±0.003, 14.06±0.002 and 15.72±0.002 bar respectively. Results were described below.

3.1 Electrical efficiency

The variation of the electrical efficiency depended on increasing syngas and MEP is shown in Figure 2. The figure indicates that the maximum electrical efficiency occurred at 14.06 bar of MEP. Use of DEE had lower electrical efficiency than diesel (as decreased to 0.75%) because DEE had lower fuel density and heating value than diesel (Table 3). While DEE and diesel were tested at equal load, the fuel consumption rate of DEE was higher than diesel led to the decrease of electrical efficiency (Sutheerasak, 2017).

When DEE is combined with syngas by compressing from 79 to 125 lpm, they are compared with using DEE and diesel show that electrical efficiency increased with increasing syngas. To compare with using DEE at maximum efficiency, increasing syngas from 79 to 125 lpm combined to DEE had electrical efficiency increased from 0.68 to 7.14% and it was increased to 6.39% to compare with diesel. This result is consistent with the outcome of Das, Dash, and Ghosal (2012) and Sutheerasak *et al.* (2019) because the combustion reaction of many syngas-air mixtures combined to DEE, which had higher oxygen (O_2) content, leading to more complete combustion resulting in decreasing the injecting DEE.

3.2 Specific energy consumption

The variation between specific energy consumption (SEC) with various gas flow rates and MEP is investigated in Figure 3. The SEC from using DEE was higher as increased to 2.84% compared with diesel at maximum efficiency. This result is consistent with the trend of Isarachewa (2006) and Sutheerasak and Chinwanitcharoen (2016) because the DEE was lower fuel density and heat of combustion than diesel which led to an increase of energy consumption as tested the equal load.

To compress the syngas combined with DEE on dual fuel, the SEC decreased with increasing syngas. Use of DEE combined to supercharging syngas from 76 to 125 lpm at maximum efficiency; the SEC was reduced from 13.26 to 10.71 MJ/kW_e.hr such that the energy-saving increased from 2.52 to 21.25% compared with using DEE only. The energy-saving increased to 19.02% when to compare with using just diesel. Results are consistent with Sutheerasak *et al.* (2019) because more complete combustion from the mixture of many syngases combined to DEE and O_2 element from the air. In addition, the main input energy used in the combustion process came from the mixture of high syngas quantity and O_2 content from air leading to the decrease of energy consumption of DEE.

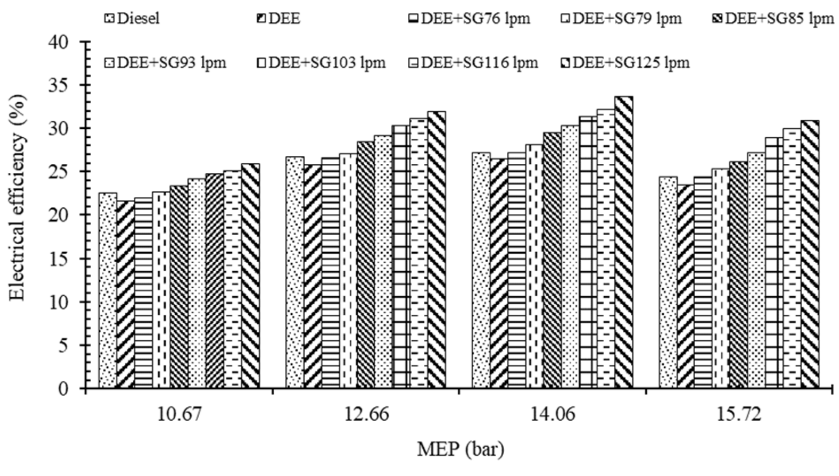

Figure 2. Electrical efficiency at various MEP.

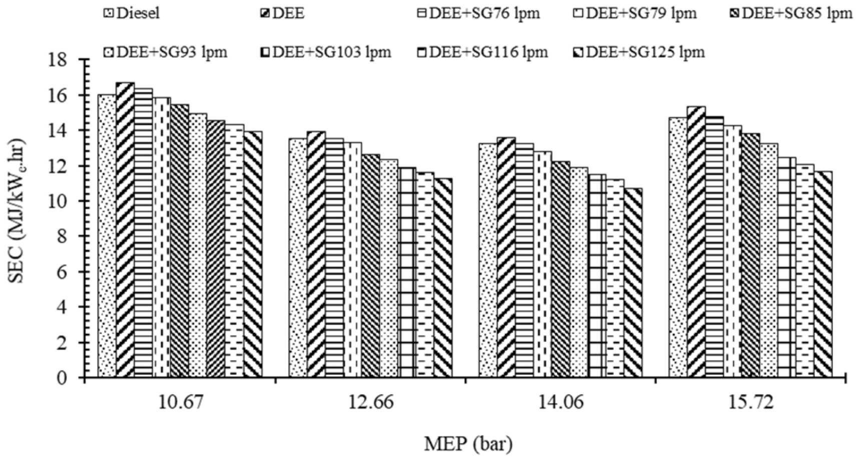

Figure 3. Specific energy consumption at various MEP.

3.3 Fuel consumption rate

Figure 4 indicates that the fuel consumption rate (FCR) increased with increasing MEP. For using DEE compared with diesel, the FCR increased to 13.80% at maximum efficiency. It can conclude that using DEE consumes more fuel than diesel which there is agreed to the past researches (Kumar *et al.*, 2013; Sutheerasak, 2017. Since the DEE was lower calorific value than diesel as tested at the engine load equaled to diesel, DEE had to be used in more fuel quantity than diesel.

However, the use of dual fuel between DEE and increasing syngas flow rate compared with only DEE and diesel are demonstrated that the FCR decreased with increasing gas flow rate. At maximum efficiency, the FCR decreased from 4.95 to 24.97% to compare with DEE, and it was reduced to 14.61% to compare with diesel. These results are consistent with Sutheerasak *et al.* (2019) and Sutheerasak *et al.* (2018) because the main fuel supply used in combustion reaction came from the mixture of lots syngas quantity and O_2 content from the air which led to the start of combustion quickly. This reason resulted in the decrease of DEE injection. Therefore, using DEE and compressing syngas on dual is more fuel saving than using DEE and diesel only. Besides, this research found that most fuel-saving occurred from using DEE+SG125 lpm at 15.72 bar of MEP by fuel saving increased to 26.40% and 15.38% to compare with the use of only DEE and diesel respectively.

3.4 Exhaust gas temperature

Figure 5 shows the trends of exhaust gas temperature (EGT) with increasing the gas flow rate and MEP. Using DEE compared to diesel confirms that the EGT is lower as decreased to 8.44 ^{o}C at maximum efficiency and this result is consistent with Sutheerasak and Chinwanitcharoen (2016) and Sutheerasak (2017). Because DEE was produced from diesel mixed to alcohol (ethanol and ethyl acetate) resulting in the rapid evaporation of DEE, it led to burn in the high premixed combustion phase and the low diffusion combustion phase. As a result, there was a decrease in combustion temperature in the diffusion combustion phase which was the main combustion period of this engine. These reasons led to a reduction in exhaust gas temperature.

Supercharging syngas and DEE on dual fuel is found that the EGT increased with increasing syngas and MEP to compare with DEE and diesel only. While examining the increasing gas flow rate and DEE on dual fuel with the DEE and diesel only at maximum efficiency indicates that the EGT increased from 16.56 to 55.89 ^{o}C and 8.11 to 47.44 ^{o}C respectively. These results are similar to Sutheerasak *et al.* (2019), and Sutheerasak *et al.* (2018) explained from the syngas properties, which had the CO_2 and CO contents (Table 2), had changed the combustion phenomenon in the diffusion combustion phase since more O_2 element was burned with a lot of syngas and DEE vapors in the period of premixed combustion. As a result, there was not enough O_2 content to burn in diffusion combustion phase resulting in the increase of late combustion phase before the exhaust valve was opened.

3.5 Carbon dioxide

Figure 6 demonstrates the levels of carbon dioxide (CO_2) increased with increasing MEP. In term of the DEE compared to diesel, the CO_2 release decreased to 0.21%vol at maximum efficiency. As consistent with Sutheerasak (2017) and Kumar *et al.* (2013), it is explained by the C/H ratio of DEE led to the change of CO_2 formation due to the existing of the O_2 molecules. As a result, the number of C molecules per volume was lower as compared to diesel. Moreover, the results of the decreasing exhaust gas temperature implied that the burning temperature from the diffusion combustion period was dropped because the main combustion reaction between DEE and O_2 content was used in the premixed combustion period.

On the other hand, the use of syngas combined to DEE increases the CO_2 level by increasing the syngas flow rate and MEP. As compared with DEE and diesel only at maximum efficiency, the CO_2 increased from 0.24 to 1.71% vol, and 0.03 to 1.50%vol, respectively. Results are consistent with Sutheerasak *et al.* (2019) and Sutheerasak *et al.* (2018) because of the composition of syngas which consisted of high CO and CO_2 quantities (Table 2) causing to incomplete combustion. Moreover, supercharging syngas decreased the O_2

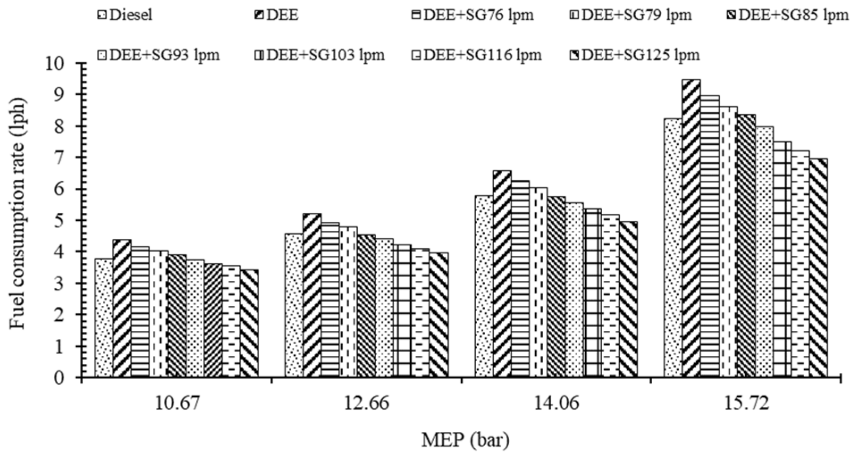

Figure 4. Fuel consumption rate at various MEP.

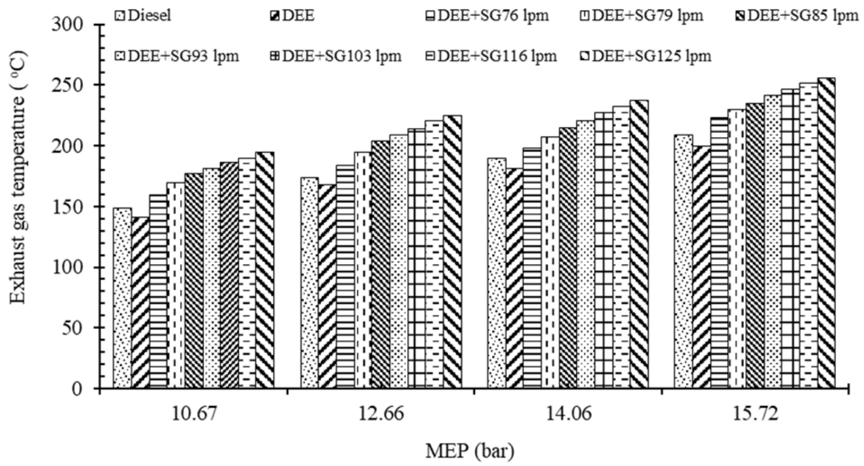

Figure 5. Exhaust gas temperatures at various MEP.

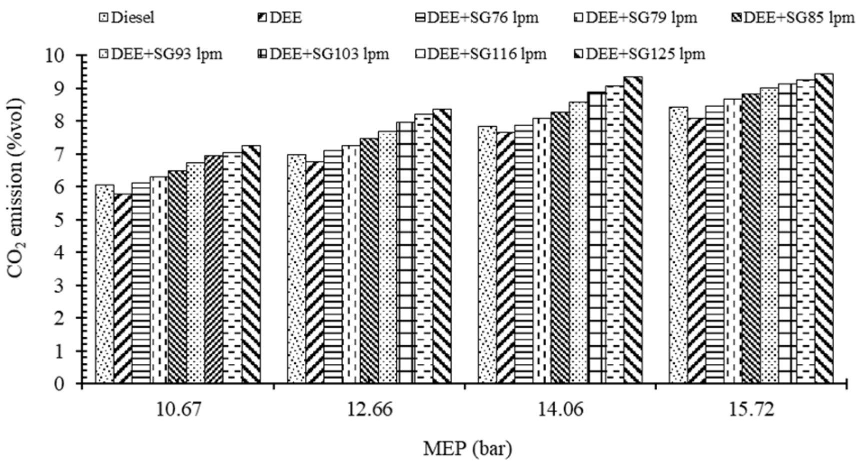

Figure 6. CO_2 levels at various MEP.

element from air flow rate sent into the combustion chamber although this research had the increase of air flow rate. Therefore, unburned syngas zone was higher than the combustion zone of syngas reacted with O_2 content. As a result, the use of DEE and increasing syngas flow rate had more CO_2 and CO release than the DEE and diesel.

3.6 Carbon monoxide

As indicated in Figure 7, the release of carbon monoxide (CO) is decreased with increasing MEP. Using DEE with this engine could reduce CO emission to 0.02 %vol compared to diesel at maximum efficiency which is agreed to the research of Sutheerasak (2017) and Kumar *et al.* (2013). Such CO reductions due to the higher complete combustion as the ethanol-ethyl acetate blend possessed more O_2 content than diesel which resulted in more complete combustion than the diesel.

Use of dual fuel between supercharging syngas and DEE provides experimental results that contrast with using DEE and diesel only. CO levels increased with increasing syngas. As compared with both oils only at maximum efficiency, CO emission increased from 0.03 to 0.24%vol, and 0.01 to 0.22%vol, respectively, while results are consistent with Su theerasak *et al.* (2019) and Sutheerasak *et al.* (2018) because the presence of CO which is the highest quantity (Table 2) from syngas composition led to the increase of incomplete combustion as explained in the release of CO_2.

3.7 Hydrocarbon

The variation between the emission of hydrocarbon (HC) with various gas flow rates and MEP is investigated in Figure 8. HC emission from using DEE was increased to 1.33 ppm compared with diesel at maximum efficiency, while this result is consistent with Kumar *et al.* (2013) hypothesized due to the higher heat of evaporation of the ethanol-ethyl acetate blend that increases the emission of HC. Such increase of HC emission, on the other hands, is agreed with the propose of the undesired unburned zone by Sutheerasak *et al.* (2019) and Sutheerasak (2017) which stated that during the fuel injection into the cylinder while as the changes of spray penetration causing unwanted fuel impingement at some areas of the cylinder wall and piston ring.

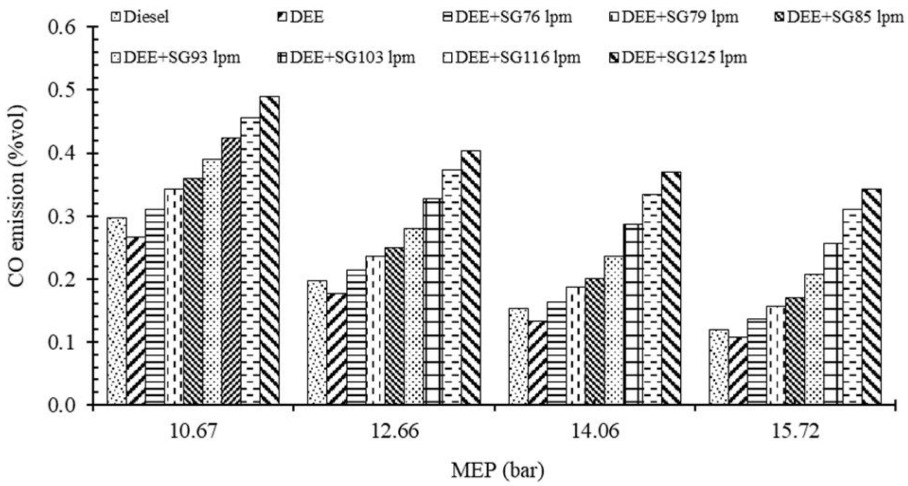

Figure 7. CO levels at various MEP.

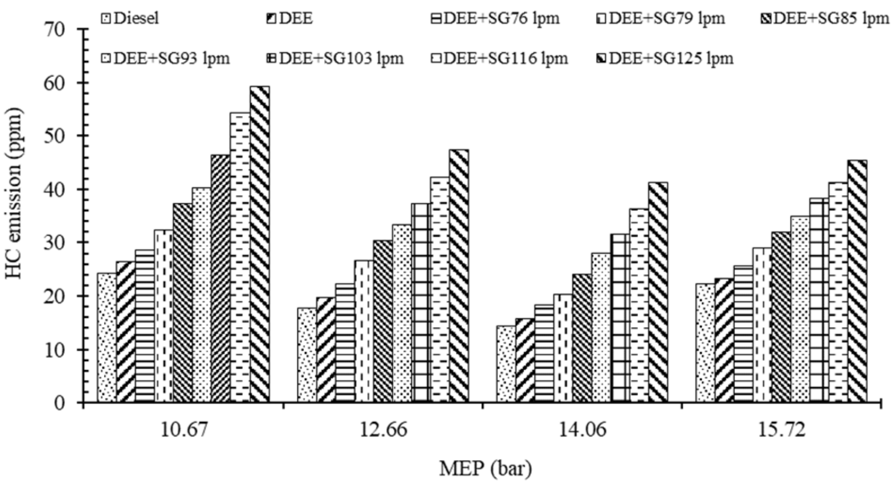

Figure 8. HC levels at various MEP.

Again, this figure indicates that supercharging syngas and DEE on dual fuel had higher HC emission than the use of both oils only. As compared with DEE and diesel only at maximum efficiency, the HC emission increased from 2.67 to 25.67 ppm and 4.00 to 27.00 ppm, respectively, while they are consistent with Sutheerasak *et al.* (2019) and Sutheerasak *et al.* (2018). It is explained from the direct result of incomplete combustion because the syngas contains the innumerable molecules of C and H which came from the composition of CO_2, CO, and CH_4. The high syngas element combined to pilot DEE will result in the combustion reaction in term of fuel rich mixture. While the amount of O_2 was burned with dual fuel between high syngas quantity and DEE, the O_2 molecules were depleted. The amount of carbon and hydrogen that were not fully combustible will form to enormous HC emission.

3.8 Black smoke

Black-smoke release is investigated from the smoke opacity shown in Figure 9. Black-smoke release trends increase as increasing MEP. Using DEE led to a low level of black smoke, as decreased to 0.24 K/m to compare with diesel at maximum efficiency. This result is consistent with Suthee rasak (2017) and Sutheerasak *et al.* (2019) because of the O_2 element in ethanol-ethyl acetate blend enhances combustion during diffusion combustion phase which subsequently reduced the smoke density.

However, compressing syngas combined to DEE indicates that the smoke opacity increased as increasing syngas and MEP. Comparing these dual fuels with using DEE and diesel only at maximum efficiency it was shown that the smoke opacity increased from 0.64 to 2.40 K/m and 0.40 to 2.16 K/m, respectively, while these results are consistent with the outcome of Sutheerasak *et al.* (2019) and Sutheerasak *et al.* (2018). Such results due to the more significant amount of C molecules from increasing syngas content while decreasing the amount of O_2 due to air flow rate dropped by compressing the gas. As a result, there was an increase in incomplete combustion and enormously release of black smoke. Moreover, the smoke opacity shows the consistent trend of the higher level of CO and HC emissions.

4. Conclusions

The turbocharging diesel engine test using DEE compared with dual fuel of DEE and supercharging syngas has been studied. The essential findings are listed below.

i) Using the DEE gave lower engine performance than diesel because of fuel density and heating value of DEE lower than DEE. To reduce the DEE restrictions; there is the use of dual fuel between DEE and supercharging syngas shown that compressing syngas has improved the engine performance. As syngas is compressed to 125 lpm to combine with DEE, the electrical efficiency increased to 7.14%. Fuel saving increased to 26.40% as compared with the use of DEE only. Use of dual fuel between DEE and supercharging syngas led to faster auto-ignition and more complete combustion resulting in decreasing the pilot DEE quantity.

ii) For investigating the engine emissions, use of DEE resulted in the lower the exhaust gas temperature, CO_2 and CO emissions, and black smoke than diesel because of more complete combustion. However, the HC emission from using DEE was higher due to the higher heat of evaporation of ethanol-ethyl acetate blend. Contrarily, the exhaust gas temperature and pollutions, such as CO_2, CO, HC, and black smoke, from using the dual fuel between DEE and compressing syngas are increased with increasing syngas. Because the insufficient O_2 element from the air was replaced by supercharging syngas, this reason led to the more incomplete combustion and the change of the premixed and diffusion combustion phase. Therefore, the formation of CO, HC, and black smoke are released galore.

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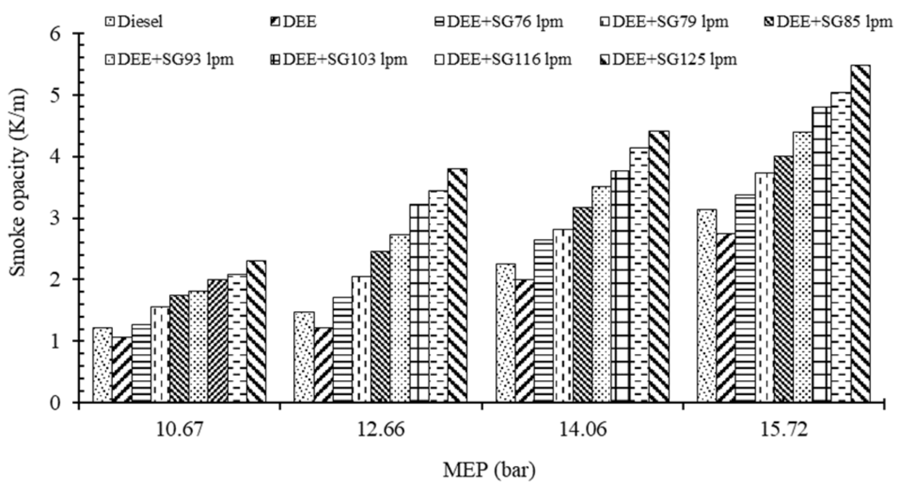

Figure 9. Smoke levels at various MEP.

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