# Investigation of PEE5 Blended with n-Butanol and Ethanol on Performance and Pollutants of a Direct Injection Diesel Engine

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**Abstract**

The research work aims to investigate the performance and exhaust emissions of a direct injection diesel engine at a constant speed of 3,000 rpm over the load range. The engine is experimentally fueled with regular diesel blended with 5% ethyl ester from palm oil (PEE5) combining with 5% n-butanol and ethanol (up to 20%), in comparison with regular diesel baseline and PEE5. Results of the engine performance test show that the brake thermal efficiency (BTE) from using PEE5 blended with 5% n-butanol and 5% ethanol increased by 0.22 and 0.31%, while the brake specific energy consumption (BSEC) decreased by 0.86 and 1.23% compared to those of regular diesel and PEE5, respectively. Engine performances when running on PEE5 blended with 5% n-butanol and 10% ethanol were comparable to regular diesel fueling. However, the use of PEE5 blended with n-butanol and ethanol added from 15 to 20% led to the reduction of BTE by up to 1.13% and the increase in BSEC by up to 4.68%. The critical findings from the exhaust gas measurements identified that the use of PEE5 blending with n-butanol and ethanol increasing from 5 to 20% resulted in the abatement of exhaust emissions, especially carbon dioxide, nitric oxide, carbon monoxide, and black smoke. The increasing concentration of oxygen and the decreasing molecules of carbon within the fuel composition led to the reduction of these emissions.

**Keywords**: engine performance, ethanol, exhaust emissions, n-butanol, PEE5

## Introduction

Nitrogen oxides ($NO_x$) and particulate matter (PM), nowadays, are causing a global serious air pollution problem. Both pollutants are mainly released from the combustion processes in internal combustion engines, particularly from diesel engines that are applied as a prime mover for various vehicles, mechanics, and generators due to their superior fuel economy and efficiency compared to gasoline engines. The PM pollutants of diesel engines, as seen by black smoke, are an important source generating significant amounts of PM2.5, the particles smaller than 2.5 micrometers in equivalent diameter. One of the main mitigation for this issue concerned by the Petroleum Research Institutes is to focus on the combination between diesel and oxygenated additives, especially esters and alcohols, due to oxygen content within both substances that can reduce these emissions (Niculescu, Clenci, & Iorga-Siman, 2019). Methods of diesel-additives combination consist of emulsification, fumigation, and modification. Emulsification is continuously being studied since this method is a mixture of two or more substances, which were usually immiscible by using a solvent that dissolved a solute resulting in a homogeneous substance. The remaining two approaches, however, are complex in their processes as the fuel injection system and the combustion chamber had to be improved (Niculescu et al., 2019; Dharma, Ong, Masjuki, Sebayang, & Silitonga, 2016; Kumar, Cho, Park, & Moon, 2013).

Previous studies on mixing diesel with both additives by emulsification are mainly focused on methyl ester (ME) and ethanol (Niculescu et al., 2019; Dharma et al., 2016). The ME is derived by transesterification of renewable oils, methanol, and catalysts, because diesel and ME have similar polarity resulting in the homogeneous phase. Ethanol is an oxygenate fermented from a variety of biomass materials, and it is a flammable polar solvent at a low price and less toxicity (Santasnachok, Sutheerasak, Ruengphrathuengsuka, & Chinwanitcharoen, 2019). Presently, diesel blended with ME from palm oil (PME) at 10%, which is regular diesel, is using in Thailand as a substitute substance to fossil diesel, according to the announcement of Thailand Energy Business Department (2019). Palm is a plant that has a high potential for fuel production than other plants because of low production cost and high palm yield per area (Sutheerasak, & Chinwanitcharoen, 2018). Kwanchareon, Luengnaruemitchai, and Jai-In (2007) studied the blends of diesel-PME-ethanol (DPE), showing that the physical properties of DPE blends were closed to diesel. Ethanol purity, however, was important on the stability of DPE blends, while they suggested that anhydrous ethanol (99.5-99.9% w/w) resulted in the completely homogeneous blends. Al-Hassan, Mujafet, and Al-Shannag (2012) analyzed the emulsion homogeneity from the stratifying time of diesel blended with ME from waste frying oil (FME) and ethanol. The most stability time occurred for the blend of 10% FME and 5% ethanol. Fuel density was increased by 0.37%, and calorific value (CV) was reduced by 4.8% compared with diesel base fuel. These results have corresponded with Sutheerasak and Chinwanitcharoen (2019) that studied the phase separation of diesel mixed with 10% palm oil ethyl ester (PEE) and 5% ethanol. However, they found that the fastest stratification time occurred after 2 hours by blending with 20% ethanol. The fuel density was similar to diesel, but the CV reduced more than 9% as compared with diesel.

Madiwale, Karthikeyan, Bhojwani, and Dombale (2017), Srinidhi, Channapatna, Pawar, and Madhusudhan (2016), and Taib, Mansor, Wan Mahmood, Shah, and Abdullah (2016) increased the proportion of PME by more than 10% in diesel blends combined with ethanol addition up to 40%. They found that the optimum ratio of DPE blends occurred at PME of less than 20% mixed with 5% ethanol due to the emulsion stability longer than 2 months. The fuel properties, specifically fuel viscosity and CV, were similar to diesel. However, the use of PME more than 20% blended with 5% ethanol had higher fuel viscosity and lower CV than diesel. Krishna, Salam, Tongroon, and Chollacoop (2019) identified that the optimum ratio of diesel blended with 17% PME and 5% ethanol similarly behaved to diesel due to its stability longer than 2 months. Niculescu et al. (2019), Ağbulut, Sarldemir, and Albayrak (2019), Ghanim, Adam, and Farouk (2018), Prbakaran and Viswanathan (2018), and Dharma et al. (2016) increased the amount of ME from renewable oils, such as cottonseed, jatropha, soybean, juliflora seeds, and waste cooking. They were increased by more than 10% by mixing with diesel combining with ethanol more than 20%. Fuel viscosity and CV declined by 59.46% and 10%, respectively, compared with diesel. Niculescu et al. (2019) and Dharma et al. (2016) founded the change in concentration of both additives in diesel blends leading to the variation of fuel properties, particularly density, viscosity, and CV, resulting in the change in engine performance. From the literature reviewed the results of diesel engines operated with blending diesel with ME from alternative oils and ethanol comparing with diesel identified that the brake thermal efficiency (BTE) reduced while the brake specific energy consumption (BSEC) increased at the ME mixture and ethanol of lower than 20%. However, the releases of carbon dioxide ($CO_2$), carbon monoxide (CO), black smoke, and nitric oxide (NO) were continuously reduced with increasing ethanol.

Kumar et al. (2013) suggested that normal butanol (n-butanol) was better as an alternative in mixing with diesel due to its superior fuel properties and miscibility than other alcohols, such as ethanol, methanol, and solvents, especially ethyl acetate, hexanol, propanol, etc. The increase of n-butanol gave lower engine emissions than these alcohols, and it led to an increase of BTE and the decrease of BSEC. Goga, Chauhan, Mahla, and Cho (2019) Emiroğlu and Şenb (2018) studied the fuel properties and the engine performance and emission, as operated with diesel blending with ME from renewable oils, such as rice bran and cottonseed, and alcohols, such n-butanol, ethanol, and methanol, up to 20%. The viscosity of these blends was increased by 20%, but the CV was decreased by 4.28% compared with diesel. Diesel blended with 20% ME and 10% n-butanol had higher BTE, and there was little lower BSEC than diesel. Moreover, this mixture had higher BTE and lower BSEC than diesel blending with other alcohols and these ME. Importantly, the releases of NO, black smoke, and total unburned hydrocarbon (HC) were lower. Sutheerasak and Chinwanitcharoen (2018) and Dharma et al. (2016) indicated that the diesel mixed with esters had higher fuel viscosity than diesel; this affects the engine-performance parameters and the change in NO release. Swamy, Chandrashekar, Banapurmath, and Khandal (2015), Doğan (2011), and Rakopoulos, Rakopoulos, Giakoumis, Dimaratos, and Kyritsis (2010) studied the blends of diesel and n-butanol (5 to 25%) on the engine characteristics. As a result, BTE and BSEC were altered from the diesel baseline. The releases of CO, NO, and black smoke were decreased, but the level of HC was increased with increasing n-butanol. Kumar et al. (2013), Prasad, Rao, and Murthy (2013) Huang et al. (2009) studied the performance and emission characteristics of a diesel engine operating with diesel mixed with 5% n-butanol and up to 30% ethanol addition. It showed to shorten the stratification time before 11 days, and there was a lower BTE than diesel due to the high addition of fuel consumption rate. The releases of CO, NO, and black smoke were decreased with increasing alcohols using n-butanol combining with ethanol. The level of HC was overwhelmingly raised. Contrariwise, diesel mixed with 5% n-butanol and ethanol lower than 20% had higher BTE than the neat diesel. Moreover, the release of HC was lower during 20% or greater ethanol addition. Previous studies on mixing diesel with esters and ethanol by emulsification are concluded in Table 1. Additionally, the mixture of 5% n-butanol can improve the engine performance.

The main objective of this study is to investigate the diesel-engine performance and exhaust emissions under constant speed and different loads, as operated with PEE5 mixed with 5% n-butanol combining with ethanol, adding up to 20% comparing with regular diesel and PEE5.

## Methods and Materials

1. Preparation of fuel blends

Preparing blends of PEE5 and 5% n-butanol combining with increasing ethanol (PBuE) by emulsion process has the processes as follows. First of all, diesel prepared for the mixtures of PEE and alcohols were regular diesel as purchased from local gas stations. This research, however, had investigated regular diesel properties, such as fuel density at 15 $^{o}$C, kinematic viscosity at 40 $^{o}$C, flash point temperature, and lower heating value (LHV), under various ASTM procedures, before blending with PEE and alcohols, since these properties affected on the change of engine-performance parameters (Niculescu et al., 2019; Dharma et al., 2016). Regular diesel (Diesel) using in this research had physical properties within the conventional diesel specifications (CDS), as announced by the Thailand Energy Business Department (2019), showing in Table 2.

**Table 1** Type of fuel blends and the advantages and disadvantages of the fuel mixture

| Fuel blends | References | Advantages | Disadvantages |
|---|---|---|---|
| Diesel-PME blends | Santasnachok et al. (2019)<br>Madiwale et al. (2017)<br>Srinidhi et al. (2016)<br>Taib et al. (2016) | -Palm is a plant that has a high potential for fuel production than other plants because of low production cost and high palm yield per area. | -PME is derived by transesterification of palm oil with methanol and catalysts, but methanol is produced from the petroleum refining at a cost.<br>-The increase of esters (PME and PEE) more than 10% leads to the decrease of engine performance as compared with diesel. Since, the increasing esters mixing with pure diesel leads to the increase of fuel viscosity and the decrease of CV, resulting in decreased engine performance and the increase of NO release. |
| Diesel-PEE blends | Santasnachok et al. (2019)<br>Sutheerasak and Chinwanitcharoen (2018) | -PEE is derived by transesterification of palm oil with ethanol and catalysts, while ethanol is an oxygenate fermented from a variety of biomass materials at low price and less toxicity.<br>-There are the completely homogeneous blends, and the diesel-PEE blends have same fuel properties and engine performance as diesel-PME blends. | |
| Diesel mixed with 10% PME and 5% ethanol | Krishna et al. (2019)<br>Srinidhi et al. (2016)<br>Kwanchareon et al. (2007) | -The fuel properties are closed to diesel, and the emulsion stability is longer than 2 months.<br>-Engine performance is little lower than diesel, but there is the decrease of exhaust gas emissions. | -Ethanol combining with oxygenated additives (esters and alcohols) cannot be increased by more than 20% due to quick stratification time before 11 days, and the engine performance is reduced with increasing ethanol. |
| Diesel mixed with 10% PEE and 5% ethanol | Sutheerasak and Chinwanitcharoen (2019)<br>Kumar et al. (2013) | | |
| Diesel blended with n-butanol and ethanol | Kumar et al. (2013)<br>Rakopoulos et al. (2010)<br>Huang et al. (2009) | -The n-butanol is superior in fuel properties and miscibility than other alcohols, such as ethanol, methanol, ethyl acetate, hexanol, propanol, etc.<br>-The adding amount of 5% n-butanol mixing with neat diesel and ethanol results in the increase of engine performance and the decrease of CO and black smoke. | The addition of n-butanol more than 5% blending with ethanol leads to the innumerable release of HC because of the increase of latent heat of vaporization from increasing alcohols leading to the increase of unburned fuels within various sources of the engine cylinder. |

Next, PEE was synthesized by transesterification of palm oil purchased from a general market and reacted with ethanol and potassium ethoxide catalyst. The purity of PEE was investigated by Gas Chromatography referred from EN14103, while the properties of PEE were studied under various ASTM procedures (Table 2). Results indicate that the yield of PEE was at 98.96%w. The properties of PEE were within the methyl ester standard specifications (MESS), as announced by the Thailand Energy Business Department, referring to Santasnachok et al. (2019). Afterward, this research produced PEE5, Diesel mixed with PEE at 5%v, because it was similar fuel properties to diesel baseline (Kalam, Masjuki, Jayed, & Liaquat, 2011; Ilkllç, Aydln, Behcet, & Aydin, 2011). Diesel at 95%v was blended with PEE at 5%v within the round bottom glass connected with the mechanical stirrer by controlling the temperature at 40 °C as studied by Sutheerasak and Chinwanitcharoen (2018). After PEE5 was completely finished, the properties of PEE5 were compared with the properties of Diesel (Table 2). PEE5 had the fuel density, viscosity, and flash point increased by 0.64%, 3.24%, 26 °C, respectively, but the LHV was only decreased by 1.00%. The properties of PEE5, however, closed to the results of Kalam et al. (2011), and they were within the CDS as announced by Thailand Energy Business Department (2019). Finally, PEE5 at 90, 85, 80, and 75%v was mixed with n-butanol (Bu) at 5%v combining with ethanol (E) at 5, 10, 15, and 20%v to produce PEE5Bu5E5, PEE5Bu5E10, PEE5Bu5E15, and PEE5Bu5E20 respectively, as studied from Sutheerasak (2017). Besides, this research produced PEE5E5, PEE5 blended with 5% ethanol, for comparison with the blends of PBuE. All mixtures were produced within the round bottom glass connected with the mechanical stirrer at a stirring rate of 1,000 rpm. The blending temperature was fixed at 30 °C, as studied by Dharm et al. (2016). After the blends of PBuE and PEE5E5 were complete, these blends were investigated fuel properties under various ASTM procedures for comparing with Diesel and PEE5. The stability of PBuE blends and PEE5E5 was analyzed from the stratification time as referred from Al-Hassan et al. (2012), Huang et al. (2009), and Kwanchareon et al. (2007) showing in Table 2 again.

**Table 2** Fuel properties

| **Items** | **Purity (%w)** | **Density ($kg/cm^3$)** | **Kinematic Viscosity ($mm^2/sec$)** | **Flash point (°C)** | **LHV (MJ/kg)** | **Stratification time[c] (days)** |
|---|---|---|---|---|---|---|
| ASTM | - | D1298 | D445 | D93 | D240 | - |
| CDS[a] | - | 810-870 | 1.8-4.1 | 52min | - | - |
| MESS[b] | 96.5min | 860-900 | 3.5-5.0 | 120min | - | - |
| Diesel | - | 826 | 3.09 | 47 | 44.37 | - |
| Ethanol | 99.90 | 792 | 1.37 | 14 | 26.43 | - |
| n-butanol | 99.50 | 810 | 2.33 | 34 | 33.18 | - |
| PEE | 98.96 | 871 | 4.72 | 173 | 39.90 | - |
| PEE5 | - | 831 | 3.19 | 73 | 43.92 | N/A |
| PEE5E5 | - | 828 | 3.13 | 71 | 43.35 | N/A |
| PEE5Bu5E5 | - | 822 | 3.06 | 16 | 42.98 | N/A |
| PEE5Bu5E10 | - | 815 | 2.99 | 14 | 42.15 | 27 |
| PEE5Bu5E15 | - | 808 | 2.83 | 12 | 41.67 | 18 |
| PEE5Bu5E20 | - | 795 | 2.71 | 9 | 40.15 | 14 |

[a]The announcement of Thailand Energy Business Department (2019)

[b]The announcement of Thailand Energy Business Department referred form Santasnachok et al. (2019)

[c]Investigating emulsion stability studied from Al-Hassan et al. (2012), Huang et al. (2009), and Kwanchareon et al. (2007)

Results of PBuE blends' properties found that they have lower fuel properties than Diesel and PEE5. PEE5 mixed with n-butanol at 5% and ethanol at 5-20% led to the decrease of fuel density, kinematic viscosity, flash point, and LHV, as reduced from 0.45 to 3.67%, 0.97 to 12.30%, 31 to 38 °C, and 3.12 to 9.51% as compared with Diesel respectively and from 1.08 to 4.28%, 4.08 to 15.05%, 57 to 64 °C, and 2.14 to 8.59% as compared with PEE5 respectively. Although the blends of PBuE will lead to the reduction of fuel properties, the fuel density and kinematic viscosity of PBuE blends are within the CDS, as announced by

Thailand Energy Business Department (2019). Comparing the properties of PBuE blends with the results of Al-Hassan et al. (2012), they have better fuel properties. The fuel density of them was lower, and the CV was higher. Additionally, this research compares the properties of PBuE blends with the properties of PEE5E5. In the case of PEE5E5 compared with Diesel, indicating that the fuel density, kinematic viscosity, and flash points were increased by 0.33%, 1.29%, and 24 $^{o}$C, respectively, but the LHV was reduced by 2.30%. For comparing PEE5E5 with PEE5, they were decreased by 0.33%, 4.00%, 2 $^{o}$C, and 1.31%, respectively. However, PEE5E5 has fuel density, and viscosity is within the CDS (Thailand Energy Business Department, 2019). Contrarily, the properties of PBuE blends, specifically PEE5Bu5E5 and PEE5Bu5E10, are within this scope, improving the fuel density and viscosity better than PEE5E5 properties, but they have lower LHV as reduced to 2.76% comparing with PEE5E5.

For analyzing the stratification time, PEE5 did not stratify because of similar polarity to diesel, leading to the homogeneous phase (Sutheerasak & Chinwanitcharoen, 2018). PEE5E5 and PEE5Bu5E5 were lasted longer 2 months before the stratification of fuel blend happened. However, PEE5Bu5E10, PEE5Bu5E15, and PEE5Bu5E20 were separated after 27 days, 18 days, and 14 days respectively. This research compares PEE5Bu5E10 with DPE10, diesel mixed with PME at 10%v and ethanol at 10%v, from the results of Al-Hassan et al. (2012). DPE10 was separated after 9 days; therefore, PEE5Bu5E10 has a longer stratification time. Besides, PEE5Bu5E10 is compared with DBE10, diesel blended with n-butanol at 5%v and ethanol at 10%v, from the results of Huang et al. (2009) showing that both blends are similar stratification time. From comparing properties of blends of PBuE with properties of PEE5E5, DPE10, and DBE10, this research identified that PEE5Bu5E5 and PEE5Bu5E10 could be suitable as an alternative fuel for diesel engines because of improving fuel properties, especially fuel density and viscosity, similar to diesel baseline. Although they have a few reductions in CV, they are no more than 3% as compared with Diesel and PEE5.

2. Diesel-engine instrumentation setup

The diesel-engine operation test using fuels were investigated at the automotive biofuels and combustion engineering research laboratory, Faculty of Engineering, Burapha University. The schematic of the experimental setup is shown in Figure 1, and the specifications of a direct-injection (DI) diesel engine using in this research are shown in Table 3.

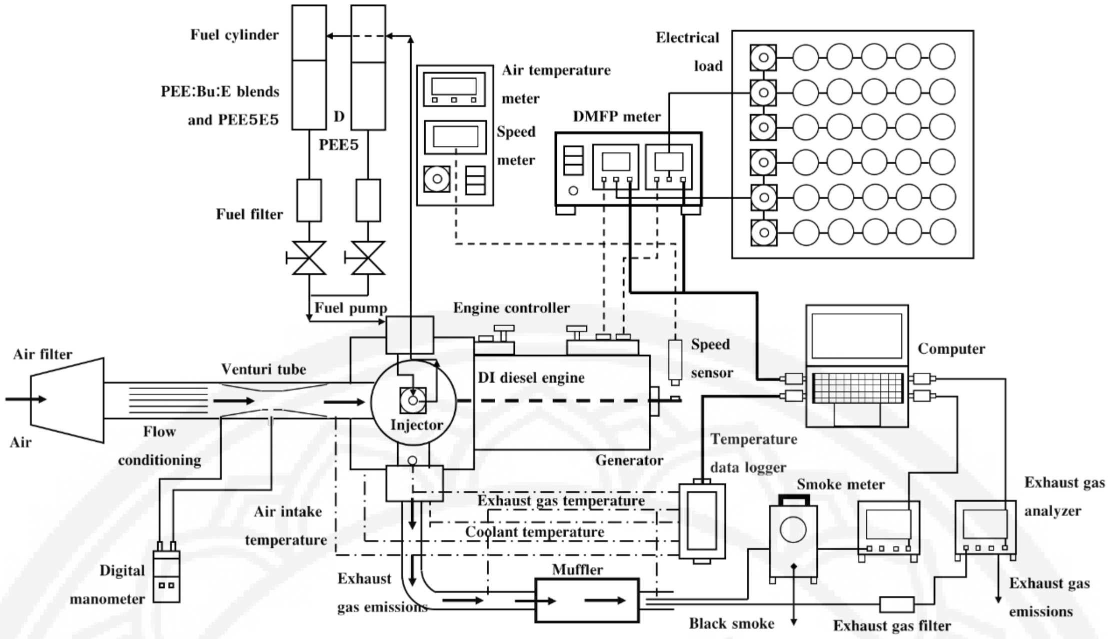


**Figure 1** Diagram of the instrumentation setup for a DI diesel engine

**Table 3** Specification of the DI diesel engine

| Item | Description |
|---|---|
| Engine model | Mitsuki: MIT-186FG |
| Engine classification | Single cylinder, 4 stroke, air coolant, and direct injection system |
| Compression ratio | 17.5:1 |
| Bore x Stroke (mm) | 86x70 |
| Maximum power (kW) | 8.5 |
| Engine speed (rpm) | 3,000 |

DI diesel engine was connected with a generator that could produce the maximum electrical power at 5 kW. For increasing engine loads, this research used a light-bulb panel, which had several bulbs connecting with this generator for adjusting loads. While the measuring brake power of this engine was in term of electrical power, this research used a digital multi-function power (DMFP) meter, which was the richtmass model: RP-96EN&RS485(MODBUS)RTU Protocol connecting with the current transformer model: IMARI-CT100/1A, for measuring the electrical power by using USB converter and hardlock for RP series as processing on a computer. For investigating the fluid temperatures, such as coolant, intake, and exhaust gas, the K-type thermocouple was connected with a temperature data logger that was an Agilent 34970A: Data acquisition as resulted in the computer by using USB converter. Fuel cylinders were used for calculating the fuel consumption from the number of fuels at 20 ml per time consumption. The air flow rate was measured from a venturi tube and a digital manometer. The exhaust emissions were investigated from an exhaust gas analyzer, the Cosber: KWQ-5 Automotive emission analyzer, by using a non-disperse infrared (NDIR) method in analyzing the release of $CO_2$, CO, and HC, and the level of NO was measured by the electrochemical cell method. The Cosber: KYD-6 Opacimeter was used to measure the percentage of black-smoke opacity. The basic characteristics of the exhaust gas analyzer and opacimeter are shown in Table 4.

**Table 4** Range and accuracy of exhaust gas measurements

| Measurements | Methods | Range | Accuracy |
|---|---|---|---|
| $CO_2$ (%vol) | NDIR method | 0-18 | ±0.02 |
| CO (%vol) | NDIR method | 0-15 | ±0.02 |
| HC (ppm) | NDIR method | 0-10,000 | ±1 |
| NO (ppm) | Electrochemical cell | 0-5,000 | ±1 |
| Black smoke (%) | Opacity | 0-100 | ±0.2 |

3. Experimental procedures

For investigating the engine performance and emission using PBuE blends compared with Diesel and PEE5, diesel engine test was studied from Goga et al. (2019) and Sutheerasak and Chinwanitcharoen (2018). All period was between 100 hours, and the results of engine performance and exhaust emissions were repeated by more than 5 times. Details of experimental procedures were as follows.

i. DI diesel engine was operated for 15 minutes before engine operation stabilization, as seen by constant engine temperatures.

ii. Experiments were started up by Diesel. The engine was continuously adjusted to the speed of 3,000±50 rpm. For determining the conditions of the engine test, there was an investigation of the air intake manifold and air surrounding temperatures as controlled at 30±5 $^{o}$C, and the cooling air temperature at the cylinder head and cylinder block walls was limited at 80±10 $^{o}$C in each condition of the engine performance test.

iii. Electrical loads were started from 20% and later 40%, 60%, 80%, and 100%, respectively, by engine temperatures were controlled according to the conditions mentioned. Fuel volume was fixed at 20 ml to record the change of time. Various parameters, such as brake power, air flow rate, fuel flow rate, temperatures, and exhaust-gas products, were recorded.

iv. After this engine operating with Diesel was finished, PEE5, PEE5E5, and PBuE blends, such as PEE5Bu5E5, PEE5Bu5E10, PEE5Bu5E15, and PEE5Bu5E20, were investigated respectively, as investigated in the same condition of Diesel.

v. All parameters recorded for all fuels were calculated in terms of the engine-performance parameters.

4. Engine-performance parameters

The engine-performance parameters are analyzed in term of brake thermal efficiency (BTE) and brake specific energy consumption (BSEC), as studied by Sutheerasak (2017). The equations were used:

$$\mathrm{BTE} = \frac{P_b}{\dot{m}_f.LHV} \tag{1}$$

$$\mathrm{BSEC} = \frac{\dot{m}_f.LHV}{P_b} \tag{2}$$

Where $P_b$ was the brake power (kW) measured in term of output electrical power from the production of electricity on each load. $\dot{m}_f$ (kg/s) was the fuel consumption rate or mass flow rate of fuels as multiplied by the density of fuels and the volume flow rate of fuels. LHV (MJ/kg) was the lower heating value of fuels.

## Results

DI diesel engine operating with fuel blends compared with Diesel and PEE5 could show various results as follows. First of all, these fuels were tested at engine speed 3,000±50 rpm as an increasing load from 20 to 100%. Brake power was increased from 1 to 5 kW, by the accuracy was between ±0.05 and ±0.27 kW. This research adjusted loads to give the equally output power from using these fuels, after that the effects of fuel blends on the performance parameters and exhaust emissions of a DI diesel engine were investigated as referring from Goga et al. (2019), Sutheerasak and Chinwanitcharoen (2018) and Huang et al. (2009).

Figure 2 indicates the brake thermal efficiency (BTE), as calculated from the brake power ratio and the total energy input, as shown in eq. (1), is increased with increasing brake power. The maximum BTE occurred at 4 kW at an 80% load. However, the brake power at 5 kW at 100% load resulted in a decrease of BTE. The trend of BTE at 100% load in this work is consistent with the results of Prbakaran and Viswanathan (2018) and Huang et al. (2009) because of the increase of mechanical frictional losses at full load leading to the increase of fuel consumption rate for producing engine power equally. Therefore, this research analyzes the effects of engine-performance parameters, BTE and BSEC, and exhaust emissions, $CO_2$, NO, CO, HC, and black smoke, from using these fuels at 4 kW brake power. However, this research shows that the use of PBuE blends in each brake power led to decreased BTE with increasing ethanol. Results of BTE from using Diesel, PEE5, PEE5E5, and PBuE blends (PEE5Bu5E5, PEE5Bu5E10, PEE5Bu5E15, and PEE5Bu5E20) at 4 kW brake power are shown in Table 5.

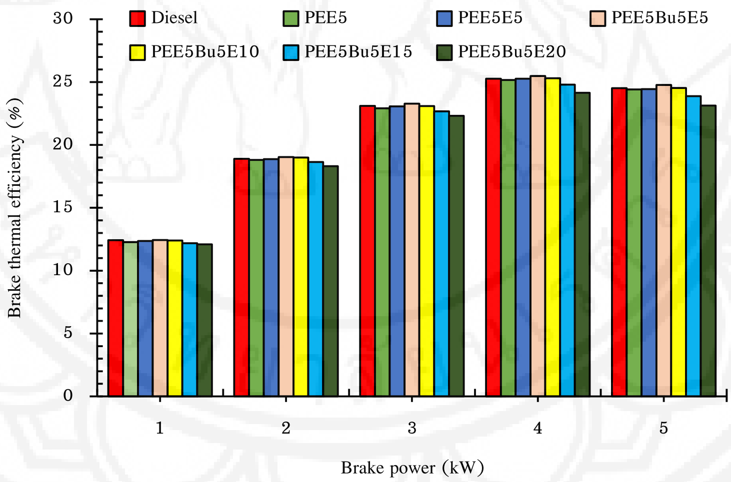


**Figure 2** Brake thermal efficiency with increasing brake power

**Table 5** Results of engine performance parameters and exhaust gas emissions

| Items | BTE[a] (%) | BSEC[a] (MJ/kW.hr) | $CO_2$[a] (%vol) | NO[a] (ppm) | CO[a] (%vol) | HC[a] (ppm) | BSO[a] (%) | BSO[b] (%) |
|---|---|---|---|---|---|---|---|---|
| Diesel | 25.26 | 14.25 | 5.19 | 530.29 | 0.0210 | 7.88 | 12.51 | 29.91 |
| PEE5 | 25.17 | 14.30 | 5.27 | 541.77 | 0.0206 | 7.63 | 12.03 | 29.16 |
| PEE5E5 | 25.27 | 14.25 | 5.23 | 534.43 | 0.0201 | 8.37 | 11.53 | 28.40 |
| PEE5Bu5E5 | 25.48 | 14.13 | 5.17 | 527.60 | 0.0198 | 9.53 | 11.08 | 27.66 |
| PEE5Bu5E10 | 25.30 | 14.23 | 5.09 | 519.67 | 0.0193 | 11.21 | 10.44 | 26.73 |

Table 5 (Cont.)

| Items | BTE[a] (%) | BSEC[a] (MJ/kW.hr) | $CO_2$[a] (%vol) | NO[a] (ppm) | CO[a] (%vol) | HC[a] (ppm) | BSO[a] (%) | BSO[b] (%) |
|---|---|---|---|---|---|---|---|---|
| PEE5Bu5E15 | 24.79 | 14.52 | 5.01 | 510.43 | 0.0188 | 13.16 | 9.65 | 25.74 |
| PEE5Bu5E20 | 24.14 | 14.91 | 4.91 | 501.93 | 0.0180 | 15.05 | 8.69 | 24.78 |

[a]Results of engine test at 4 kW brake power

[b]Results of engine test at 5 kW brake power

Variation between brake specific energy consumption (BSEC) with increasing brake power is shown in Figure 3. The BSEC was calculated from the total energy input ratio and the brake power, as shown in eq. (2). BSEC is reduced with increasing brake power, whereas the minimum BSEC occurred at 4 kW brake power. However, the BSEC at 5 kW brake power was increased as corresponded with the decrease of BTE described in the previous paragraph. Therefore, the best engine performance occurs at 4 kW brake power. The use of PBuE blends in each brake power had an increase of BSEC with increasing ethanol. Results of BSEC from using Diesel, PEE5, PEE5E5, and PBuE blends at 4 kW brake power are numerated in Table 5.

Carbon dioxide ($CO_2$) is formed by the complete combustion of carbon concentration within fuels reacted with sufficient oxygen, and it is the main product from the exhaust gas of engines (Pundir, 2007). However, the release of $CO_2$ extremely affects global warming and the greenhouse effect, and it is necessary to measure the $CO_2$ release from this engine. As indicated in Figure 4, the levels of $CO_2$ are accrued with increasing brake power. The use of PBuE blends in each brake power had the abatement of $CO_2$ with increasing ethanol. The releases of $CO_2$ from using Diesel, PEE5, PEE5E5, and PBuE blends at the best engine performance are shown in Table 5.

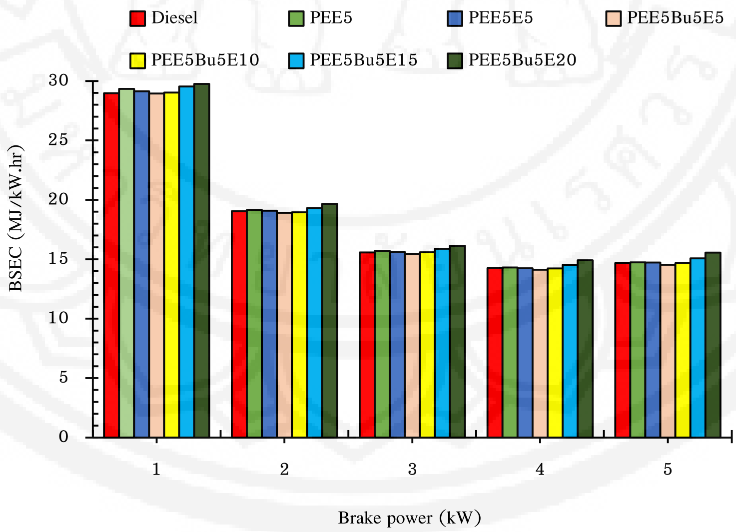


**Figure 3** BSEC with increasing brake power

Nitric oxide (NO) is a common designation of nitrogen oxides formed in high flame temperatures and more oxygen concentration (Huang et al., 2009). Trends of NO from using fuel blends are demonstrated in Figure 5; the releases of NO are enlarged with increasing brake power. However, the use of PBuE blends in each brake power led to the reduction of NO emission with increasing ethanol. Results of NO releases from using Diesel, PEE5, PEE5E5, and PBuE blends at the best engine performance are demonstrated in Table 5.

Carbon monoxide (CO) is the result of the incomplete combustion of hydrocarbons available in fuels and the reduction of air-fuel (AF) ratio (Goga et al., 2019). Trends of CO release are shown in Figure 6, and the amount of CO emission is decreased with increasing brake power. The releases of CO at 5 kW brake power, however, was increased as corresponded with the decrease of BTE since the fuel consumption was increased with increasing brake power. Moreover, the amount of air entering this engine was little changed at a constant speed of 3,000 rpm, resulting in decreased AF ratio. As a result, the incomplete combustion of fuel rich mixture was increased, resulting in increasing CO release (Pundir, 2007). This research found that the use of PBuE blends in each brake power resulted in decreased CO emissions with increasing ethanol. Results of CO emissions from using Diesel, PEE5, PEE5E5, and PBuE blends at the best engine performance are numerated in Table 5.

Unburned hydrocarbon (HC) is formed by the unburning independent decomposition of carbon-hydrogen molecules ratio that is in the main constituents of petroleum fuels surrounding a combustion chamber (Goga et al., 2019). The levels of HC with increasing brake power from using fuel blends are investigated in Figure 7, showing that HC emissions are reduced with increasing brake power. However, this research identified that the use of PBuE blends in each brake power led to HC's addition with increasing ethanol. The releases of HC from using Diesel, PEE5, PEE5E5, and PBuE blends at the best engine performance are shown in Table 5.

Finally, the black-smoke quantity is an important source generating significant amounts of PM2.5 as resulted from a mass of impure carbon particles resulting in the incomplete combustion of hydrocarbons, which helps in originating smoke opacity (Niculescu et al., 2019; Goga et al., 2019).

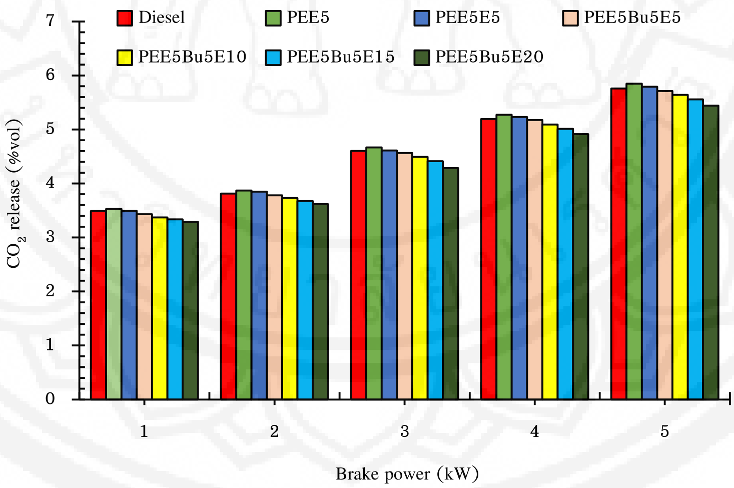


**Figure 4** Level of $CO_2$ with increasing brake power

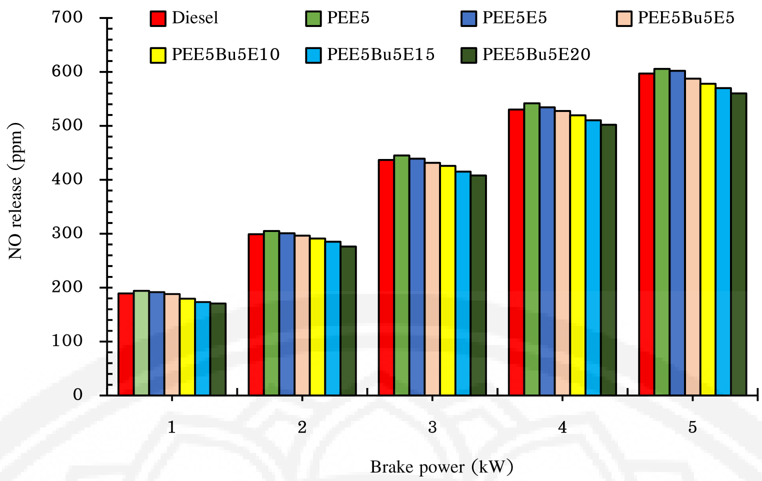


**Figure 5** Level of NO with increasing brake power

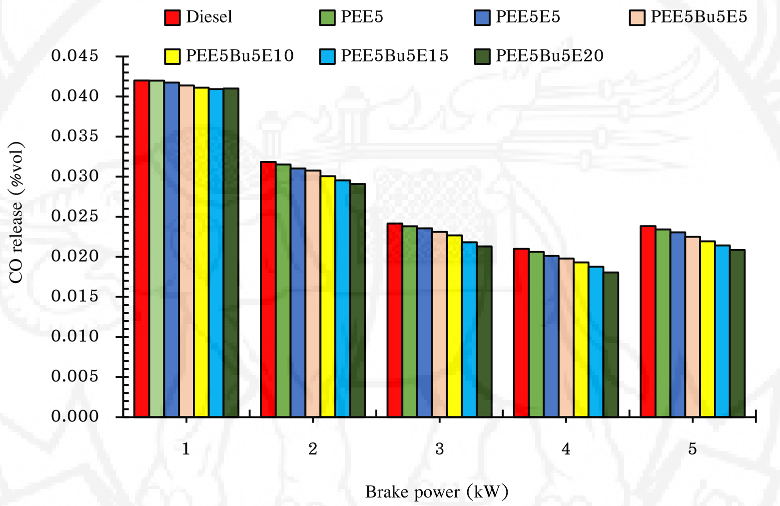


**Figure 6** Level of CO with increasing brake power

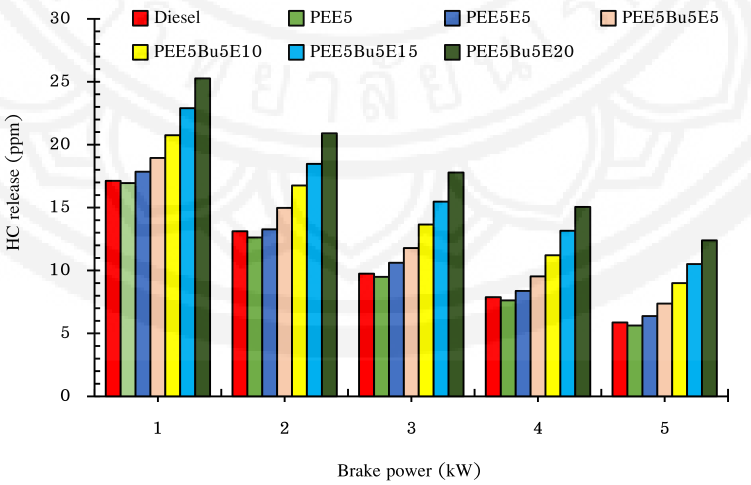


**Figure 7** Level of HC with increasing brake power

This research investigates the black-smoke release from the percentage of black-smoke opacity (BSO), which is an unintended measurement of soot particles' existence in the exhaust emission, as shown in Figure 8. Trends of BSO are increased with increasing brake power due to the low AF ratio and the high utilization of fuel (Goga et al., 2019). The use of PBuE blends in each brake power found that the black-smoke quantity was reduced with increasing ethanol. The levels of BSO from using Diesel, PEE5, PEE5E5, and PBuE blends at the brake powers of 4 and 5kW are identified in Table 5.

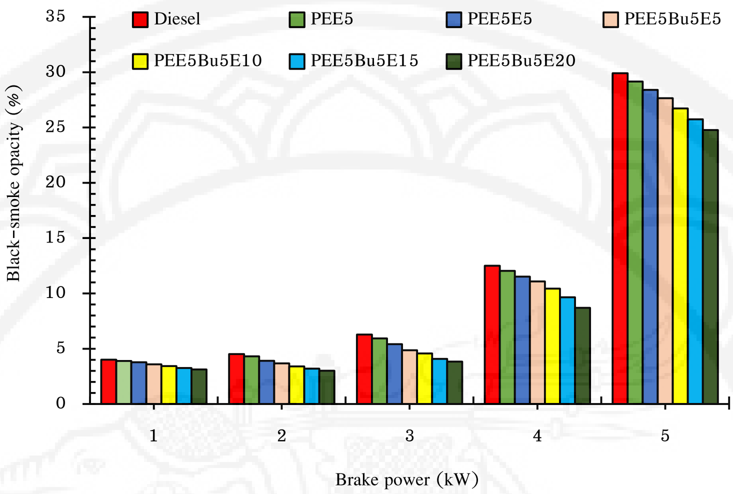


**Figure 8** Level of black-smoke opacity with increasing brake power

## Discussion

The use of PBuE blends for the DI diesel engine at 3,000 rpm and various loads leads to the change of engine-performance parameters and exhaust emissions, as described below.

1. Brake thermal efficiency

Brake thermal efficiency (BTE) from using fuel blends is changed as follows. (i) The use of PEE5 has lower BTE than Diesel, as reduced by 0.09% because of lower LHV than Diesel (Table 1), leading to the increase of fuel consumption rate as testing at the same brake power causing the curtailment of BTH (Sutheerasak & Chinwanitcharoen, 2018). (ii) The use of PEE5E5 has a little higher BTH than Diesel, as added by 0.01%. Because the increased oxygen concentration from using ethanol combined with PEE5 led to more complete combustion occurring in the diffusion combustion zone, hence improving the BTH (Sutheerasak & Chinwanitcharoen, 2019). (iii) The use of PEE5Bu5E5 and PEE5Bu5E10 identified that the BTE increased by 0.22 and 0.04%, 0.31 and 0.13%, and 0.21 and 0.03% compared with Diesel, PEE5, and PEE5E5, respectively. The best BTE occurred from using PEE5Bu5E5, and PEE5Bu5E10 had BTE closed to Diesel but a little higher than PEE5 and PEE5E5. These results were similar to the results of Rakopoulos et al. (2010) and Huang et al. (2009), as explained by the addition of n-butanol combining with ethanol lower than 10% reduced the ignition delay period resulting in the increase of complete combustion in premixed and diffusion zones leading to the increase of BTE. (iv) The use of PEE5Bu5E15 and PEE5Bu5E20 has the opposite results using PEE5Bu5E5 and PEE5Bu5E10, demonstrating that the BTE was reduced by 0.47 and 1.12%, 0.38 and 1.03%, and 0.48 and 1.13% as compared with Diesel, PEE5, and PEE5E5, respectively.

These results are consistent with Kumar et al. (2013) and Al-Hassan et al. (2012), as clarified by the increase of alcohols (n-butanol and ethanol) more than 10% led to the more reduction of CV resulting in an increase in the volume of fuel injected to maintain the same engine power. Therefore, the brake power from using blends of PBuE was produced equaling with Diesel, PEE5, and PEE5E5, but the input energy was increased, resulting in the reduction of BTE. However, the BTE from using the PBuE blends is better than the results of Al-Hassan et al. (2012) and Huang et al. (2009), since the adding n-butanol at 5% improved in the premixed combustion zone leading to higher combustion in constant volume process and in diffusion zone resulting in lower heat losses from combustion in constant pressure (Rakopoulos et al., 2010).

2. Brake specific energy consumption

The use of PEE5 and PEE5E5 comparing with Diesel shows that the brake specific energy consumption (BSEC) was different. PEE5 had higher BSEC than Diesel, as increased by 0.37%. It was explained by the fuel-consumption addition from reducing the CV of PEE5 as tested at the same brake power led to the increase of BSEC (Sutheerasak & Chinwanitcharoen, 2018). On the other hand, PEE5E5 reduced BSEC by 0.04% comparing with Diesel, as clarified by the combination between PEE5 and ethanol lower than 10% had higher oxygen concentration than PEE5, resulting in the more complete combustion within diffusion combustion phase. Therefore, there was a decrease in the main injection period leading to the fuel-consumption reduction, although there was a reduction of CV. As a result, the total energy input was decreased as testing at the same brake power resulting in the BSEC reduction (Sutheerasak & Chinwanitcharoen, 2019).

The results of BSEC from using blends of PBuE indicate that the BSEC was increased with increasing ethanol, although n-butanol was added by 5%. Nevertheless, the PBuE blends led to the change of BSEC as compared with Diesel, PEE5, and PEE5E5 as follows. In the case of using PEE5Bu5E5 and PEE5Bu5E10, the BSEC was reduced by 0.86 and 0.16%, 1.23 and 0.53%, and 0.82 and 0.12% as compared with Diesel, PEE5, and PEE5E5, respectively. The decrease of these results was assumed by the BSEC as inversely proportional to the BTH, while the BTH was increased, leading to the reduction of BSEC (Sutheerasak, 2017). Additionally, these results were similar to Kumar et al. (2013) and Rakopoulos et al. (2010). They were explained by the combination between n-butanol and ethanol lower than 10% led to high oxygen content resulting in more complete combustion within premixed and diffusion zones. As a result, the fuel injection rate within these zones was reduced, leading to a decrease in fuel consumption rate. The brake power was equally produced, but the total energy input, which was the multiplication between fuel consumption rate and CV, was reduced. Therefore, the BSEC was reduced. In terms of using PEE5Bu5E15 and PEE5Bu5E20, the BSEC was added by 1.90 and 4.64%, 1.52 and 4.25%, 1.94 and 4.68% as compared with Diesel, PEE5, and PEE5E5, respectively. These results were consistent with Kumar et al. (2013) and Huang et al. (2009), as explained by the increase of alcohols more than 10% led to the more reduction of LHV. Although the use of PEE5Bu5E15 and PEE5Bu5E20 was improving better in these zones, the CV of PEE5Bu5E15 and PEE5Bu5E20 was much lower than Diesel, PEE5, and PEE5E5 (Table 1). As a result, there was the addition of the fuel consumption rate. Therefore, the total energy input of PEE5Bu5E15 and PEE5Bu5E20 was higher than Diesel, PEE5, and PEE5E5 leading to an increase of BSEC.

3. Carbon dioxide

The use of PEE5 and PEE5E5 comparing with Diesel shows that the release of carbon dioxide ($CO_2$) was changed. The use of PEE5 leads to the escalation of the $CO_2$ level, as increased by 1.56%. This result was consistent with Niculescu et al. (2019), since the empirical formula of PEE5 shows more carbon and oxygen concentration than Diesel. It was reacted with oxygen molecules of air surrounding the combustion chamber, causing the more accretion of $CO_2$ product. However, the use of PEE5E5 has a few $CO_2$ release additions, as added by 0.75% compared with Diesel. Because the combination between PEE5 and 5% ethanol led to increased oxygen concentration, the complete combustion was highly increased in the premixed combustion phase increasing $CO_2$ release. Nevertheless, the use of PEE5E5 had less carbon molecules within the fuel element than PEE5 due to the mixture of ethanol, leading to a decrease of carbon molecules. Therefore, PEE5E5 had a lower $CO_2$ release than PEE5 (Dharma et al., 2016).

Moreover, the level of $CO_2$ from using blends of PBuE was decreased with increasing ethanol combining with n-butanol. The level of $CO_2$ from using PEE5 mixed with 5% n-butanol and ethanol adding from 5 to 20%v was reduced from 0.31 to 5.34%, 1.82 to 6.78%, and 1.07 to 6.06% as compared with Diesel, PEE5, and PEE5E5, respectively. These results are the same as the results of Ghanim et al. (2018), Madiwale et al. (2017), Dharma et al. (2016), and Kumar et al. (2013), as assumed by the numerous escalation of hydrogen (H) and oxygen (O) concentrations (H-O concentrations) and the dramatic reduction of carbon molecules within the element of PEE5 mixed with increasing alcohols. These blends were reacted with the oxygen molecules of air surrounding the engine cylinder resulting in the formation of oxidizing species in terms of hydroxyl radical (OH) increasing with adding alcohols. As a result, the fewer molecules of carbon reacted with oxygen molecules led to the release of $CO_2$ decreased with increasing alcohols. Importantly, the use of PEE5Bu5E5 and PEE5Bu5E10 could reduce the $CO_2$ release compared with PEE5 and PEE5E5. They were explained by the formation of $CO_2$ from one carbon atom reacting with two oxygen atoms. Still, both blends had fewer carbon molecules within fuel elements than PEE5 and PEE5E5 because of the dwindling molecules of carbon reducing with increasing alcohols. As a result, the formation of $CO_2$ was decreased with increasing alcohols (Dharma et al., 2016; Kumar et al., 2013). For comparing PEE5Bu5E5 and PEE5Bu5E10 with Diesel, the level of $CO_2$ was only relieved by 0.31 and 1.95%, respectively. Therefore, PEE5Bu5E5 and PEE5Bu5E10 had lower $CO_2$ release than PEE5 and PEE5E5.

4. Nitric oxide

The use of PEE5 and PEE5E5 was higher nitric oxide (NO) release than Diesel, even though the ethanol was at 5% blending with PEE5. They were increased by 2.17 and 0.78%, respectively. Because the oxygen concentration depended on using PEE5 and PEE5E5 may cause a highly burning reaction in the premixed combustion zone by enhancing the flame speed in this zone, it led to increased burning temperature. More oxygen molecules that originate from the fuel blends may expand the premixed combustion duration, providing a longer time for NO formation (Niculescu et al., 2019; Dharma et al., 2016). However, the use of PEE5E5 had less NO release than PEE5. Sutheerasak and Chinwanitcharoen (2019) and Dharma et al. (2016) explain that NO is formed in high flame temperatures and more oxygen concentration. Still, the use of PEE5 blended with ethanol led to the quick flame propagation in premixed and diffusion zone resulted in the reduction of flame temperature. As a result, the level of NO from using PEE5E5 was lower than PEE5.

Moreover, the NO level dwindled with increasing alcohols, using 5% n-butanol combined with ethanol increasing from 5 to 20%. For comparing the PBuE blends with Diesel, PEE5, and PEE5E5, the NO level was decreased from 0.51 to 5.35%, 2.62 to 7.35%, and 1.28 to 6.08%, respectively. These results are the opposite of the results of Ağbulut et al. (2019), Ghanim et al. (2018), and Prbakaran and Viswanathan

(2018), as used the pure diesel mixed with increasing ME and ethanol. As a result, the increase of ME mixing with constant ethanol led to the increase of flame temperature in the premixed zone resulting in the addition of NO, as explained by Dharma et al. (2016). However, these results are the same as the results of Emiroğlu and Şen (2018), Goga et al. (2019), Gnanamoorthi and Devaradjane (2013), Rakopoulos et al. (2010), and Huang et al. (2009). Because they studied the blends of pure diesel, esters, and increasing alcohols, they hypothesized by continuously reducing carbon concentrations and adding H-O concentrations from constant esters blending with the numerous alcohols. As a result, the cumulative addition of OH formation was increased, leading to an increase of vapor water ($H_2O_{(g)}$). Simultaneously, the rapid vaporization rate of alcohols was added with increasing alcohols, resulting in decreased auto-ignition temperature. As a result, the flame temperature in the premixed combustion phase was reduced, leading to the reduced NO release as increasing alcohols. Nevertheless, the comparative PEE5Bu5E5 and PEE5Bu5E10 with Diesel show that the NO level was reduced by 0.51 and 2.00%, respectively. On the other hand, the level of NO was increased using PEE5 and PEE5E5. Therefore, the use of PEE5Bu5E5 and PEE5Bu5E10 had lower NO emission than PEE5 and PEE5E5 due to the high addition of alcohols leading to expeditious flame propagation in premixed and diffusion zones resulted in the quick reduction of flame temperature with increasing alcohols (Kumar et al., 2013).

5. Carbon monoxide

Results from measuring the carbon monoxide (CO) emission indicate that the level of CO emission from using PEE5 and PEE5E5 was lower than Diesel, as reduced by 1.83 and 4.15%, respectively. These results were similar to results of Niculescu et al. (2019) and Dharma et al. (2016), as clarified by the increasing concentration of oxygen and the decreasing molecules of carbon within the fuel composition reacting with the amount of oxygen from the element of surrounding air leading to more complete combustion. As a result, the carbon molecules were reacted with the more molecules of oxygen to release the amount of $CO_2$ more than CO. Moreover, the combination between PEE5 and 5% ethanol led to the highly addition of oxygen molecules, and the molecules of carbon dropped dramatically. As a result, this fuel blend was reacted with the oxygen content from surrounding air resulting in the extremely complete combustion leading to the decrease of CO formation.

Additionally, the CO release from using PBuE blends is reduced with increasing alcohols. CO from using PEE5 mixed with 5% n-butanol and ethanol added from 5 to 20% was relieved from 5.79 to 14.11%, 4.03 to 12.50%, and 1.71 to 10.39% as compared with Diesel, PEE5, and PEE5E5, respectively. These results are the same as the results of Emiroğlu and Şen (2018), Goga et al. (2019), Dharma et al. (2016), Gnanamoorthi and Devaradjane (2013), Rakopoulos et al. (2010) and Huang et al. (2009), since the addition of alcohols combining with PEE5 led to the dramatic reduction of carbon molecules. The numerous escalations of oxygen molecules encouraged copiously complete combustion. It resulted in lower CO emission than the use of Diesel, PEE5, and PEE5E5. CO emission from using PEE5Bu5E5 and PEE5Bu5E10 was reduced by 5.79 and 8.06% as compared with Diesel, respectively. Therefore, the use of PEE5Bu5E5 and PEE5Bu5E10 had lower CO emission than PEE5 and PEE5E5.

6. Unburned hydrocarbons

This research indicates that the release of unburned hydrocarbons (HC) from using fuel blends was changed as follows. (i) The use of PEE5 comparing with Diesel shows that the HC release was dropped by

0.25 ppm because of the complete combustion from increasing oxygen content of 5% PEE (Niculescu et al., 2019; Dharma et al., 2016). (ii) The level of HC was increased from using PEE5E5, as added by 0.50 ppm as compared with Diesel. Since the mixing ethanol with PEE5 had higher latent heat of vaporization, it led to the increase of unburned fuels within various sources of the engine cylinder resulting in more HC emission (Niculescu et al., 2019; Dharma et al., 2016). (iii) HC emission from using PBuE blends is raised with increasing alcohol. Use of PEE5 mixed with 5% butanol and 5-20% ethanol increased the HC emission from 1.65 to 7.17 ppm, 1.90 to 7.42 ppm, and 1.16 to 6.68 ppm as comparing with Diesel, PEE5, and PEE5E5, respectively. These results are similar to the results of Emiroğlu and Şen (2018), Goga et al. (2019), Sutheerasak and Chinwanitcharoen (2019), Dharma et al. (2016), Gnanamoorthi and Devaradjane (2013), Rakopoulos et al. (2010) and Huang et al. (2009), as supposed by the formation of HC primarily originated from the unburned fuel accumulation within various parts of the engine cylinder. In particularly, the areas of ring pistons and chamber walls. The adding alcohols caused the higher latent heat of vaporization, leading to the accretion of accumulating fuel vapor within the cylinder, becoming an inferior fuel-oxygen combustion because some fuel vapor was partially burned with oxygen. As a result, there was a significant accumulation of unburned fuels within various parts of the engine cylinder. These reasons led to an increase in the HC level. The release of HC from using PEE5Bu5E5 and PEE5Bu5E10 was added to 1.65 and 3.33 ppm compared with Diesel, respectively. Therefore, the use of PEE5Bu5E5 and PEE5Bu5E10 had a little higher HC emission than PEE5 and PEE5E5.

7. Black-smoke opacity

Results from measuring the black-smoke opacity explaining the black smoke release are demonstrated that the level of black-smoke opacity from using PEE5 and PEE5E5 comparing with Diesel was reduced by 2.53 and 5.05%, respectively. These results are similar to the results of Niculescu et al. (2019) and Dharma et al. (2016) due to more oxygen molecules within both fuels leading to better combustion in the diffusion zone, causing the dwindling smoke opacity and decreasing black smoke emission. Moreover, the level of black-smoke opacity from using blends of PBuE is reduced with increasing alcohols. The level of black-smoke opacity from using PEE5 mixed with 5% butanol and 5-20% ethanol at full load, which had the most black-smoke opacity, was reduced from 7.52 to 17.16%, 5.14 to 15.03%, and 2.61 to 12.75% as compared with Diesel, PEE5, and PEE5E5 respectively. These results are the same as the results of Ağbulut et al. (2019), Emiroğlu and Şen (2018), Goga et al. (2019), Ghanim et al. (2018), Dharma et al. (2016), Gnanamoorthi and Devaradjane (2013), and Rakopoulos et al. (2010), since the fact that the increase of alcohols mixing with PEE5 led to the lesser carbon molecules reduction and the more oxygen molecules accretion. These results had changed in the combustion phenomena of the diffusion zone, which was continuously complete combustion with increasing alcohols, leading to the lessening black smoke. Besides, these results correspond to the decrease of CO emission, as shown in the section on CO emission. Furthermore, the use of PBuE blends, particularly PEE5Bu5E5 and PEE5Bu5E10, had a lower level of black-smoke opacity than PEE5 and PEE5E5. Because the use of PEE5Bu5E5 and PEE5Bu5E10 led to the reduction of black-smoke opacity at 7.52 and 10.64% compared with Diesel. The use of PEE5Bu5E5 and PEE5Bu5E10 had a lower level of black-smoke opacity than PEE5 and PEE5E5.

## Conclusion and Suggestions

From investigating the performance and exhaust emissions of a direct-injection diesel engine by using PBuE blends compared with Diesel and PEE5 at 3,000 rpm and different loads, the main results can be concluded as the followings:

1. The use of PBuE blends resulted in the reduction of BTE and the increase of BSEC continuously because the increase of ethanol led to the decrease of fuel properties, particularly fuel density and LHV, resulting in the addition of fuel consumption rate at the equal brake power. However, the use of PEE5Bu5E5 and PEE5Bu5E10 gave the BTE higher than Diesel and PEE5, and there is a decrease of BSEC. This research indicates that the use of PEE5Bu5E5 had the best BTE as increased by 0.22 and 0.31%, and the BSEC was reduced by 0.86 and 1.23% compared with Diesel and PEE5, respectively.

2. Trends of exhaust emissions, $CO_2$, NO, CO, and black smoke, from using PBuE blends, identified that they reduced such pollutants because of the dramatic reduction of carbon molecules and the numerous additions of OH formation. And with increasing ethanol resulting in the decrease of auto-ignition temperature and the rapid combustion in premixed and diffusion zones leading to the abatement of these emissions.

3. This research found that the accretion of HC emission was yet increased with increasing ethanol. However, there was a combination between PEE5 and n-butanol because ethanol had higher latent heat of vaporization than n-butanol and PEE5, leading to the numerous accumulations of HC within various sources of the combustion chamber.

To further complement the presented study, the following suggestions can be adopted in the future:

1. The injection and combustion characteristics from using blends of PBuE compared with Diesel and PEE5 would be conducted to support the results of engine-performance parameters and exhaust emissions discussed in this research work.

2. Since this research work identified that PEE5Bu5E5 and PEE5Bu5E10 was better for engine performance than Diesel and PEE5, the analyses of wear in diesel engines as operating with both fuels compared with Diesel and PEE5 in long term usage are recommended for exploration.

3. As the application of various types of fuel from the test results have been disclosed, the economics for real usage would be analyzed for future work.

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