Emissions from High-Speed Direct Injection Diesel Engines Using Palm Ethyl Ester Fuel Produced with Potassium Ethoxide Catalyst

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Abstract—**Particle pollution released from diesel engines is an important environmental concern. A replacement of regular diesel by fatty acid esters is continuously studied to reduce pollutants. This paper presents the experimentation of Palm Ethyl Ester (PEE) and its blends, running on a High-Speed Direct Injection (HSDI) diesel engine at a constant speed of 3,000 rpm under various electrifications. PEE was transesterified by palm olein and anhydrous ethanol under the alcohol/oil molar ratio of 6:1 catalyzed by potassium ethoxide at 1%. The neat and blended PEE in regular diesel indicated the reduction of exhaust emissions in the HSDI engine. The unburned hydrocarbons, carbon monoxide, black smoke, and particulate matter were reduced by 30%, 49%, 36%, and 45%, respectively. The nitric oxide was elevated by 14%. Additionally, the brake thermal efficiency decreased, and the brake specific fuel consumption increased by 9% and 24%, respectively. The PEE blended with increasing regular diesel led to the improvement of engine performance and the decrease of nitric oxide according to regular diesel proportions increased.**

Keywords—**engine performance, exhaust emissions, HSDI diesel engine, PEE, regular diesel**

I. INTRODUCTION

Fine particulate matter is a major air pollution issue that must be solved urgently, since it leads to increasing mortality from all causes, cardiovascular disease, respiratory disease, and lung cancer. The primary outdoor source comes from using various diesel engines, mostly applied to automobiles, generators, locomotives, machines, and ships. They inherently burn the mixture of hydrocarbon fuel and air, particularly in diffusion combustion mode. Particulate Matter (PM) and black carbon are highly concentrated in this scenario due to the likelihood of producing Unburned Hydrocarbons (UHC), Carbon Monoxide (CO), and Black Smoke (BS) [1, 2]. In addition, the issue of crude oil shortages is continuing to intensify. This issue leads to an increase in crude oil prices. A replacement of hydrocarbon fuel by biofuels has been, therefore, established as they can improve the UHC, CO, BS, and PM emissions and be procured from raw materials of various renewable resources [3, 4]. Fatty acid esters are a renewable biofuel produced by transesterifying feedstock materials and alcohols via catalysts. They are receiving a lot of attention in continuous development, because they can be produced from edible and non-edible plant oils, animal fats, and waste frying oils leading to a reduction in the impacts of black carbon and the need for foreign oil [5–7].

Fatty Acid Methyl Ester (FAME) is produced from fatty-acid oils, methanol, and catalysts by transesterification, as studied in the beginning due to the low cost, quick reaction rate, and high ester yield. The diesel-engine performance and emission from using FAME and its blends showed a slight difference compared with diesel [8–10]. Palm methyl ester (PME) is a FAME made by transesterifying palm oil, methanol, and catalysts, because palm oil is an important raw material in the local market of Continental Southeast Asia. Previous studies on PME preparation usually used molar ratios of methanol to palm oil ranging from 6:1 to 12:1, catalyst amounts less than 5%, and reaction temperatures between 60 and 70 ºC, as the ester yields were more than 95%. Potassium hydroxide (KOH) and sodium hydroxide (NaOH) were used as superior alternative catalysts due to their low cost and optimum methanol/palm oil molar ratio [11–14]. Palm oil used in transesterification processes has various kinds, such as crude palm oil, palm kernel oil, palm olein, etc. The key factors of ester yield from palm oil are based on reactant purity, blending time, reaction temperature, catalyst type and concentration, and alcohol/oil molar ratio. Palm olein was selected because of its cleanliness, purity, and ease of supply. The PME yield were more than 98% by using the alcohol/oil molar ratio at 6:1 under 1% catalysts, mixing time at 60 min, and reacting temperature lower than 70 ºC. PME-fueled diesel engines reported a minor decrease in performance and wear but a greater reduction in exhaust emissions, when compared to the diesel baseline in an experimental examination [8–14].

However, methanol is produced from a variety of sources, especially petroleum refining of crude oil, leading to an increase the impacts of global warming. Global warming mainly results from the increasing concentration of carbon dioxide (CO_2). The maximum global warming potential for using methanol is reported at 2.97 kg of CO_2 per 1 kg of methanol [15], but the global warming potential form using ethanol ranges from 0.31 to 5.55 kg of CO_2 per 1 kg of ethanol [16]. Palm oil and non-oxidative ethanol are transesterified using a catalyst to create Palm Ethyl Ester (PEE), an ester in the case of Fatty Acid Ethyl Esters (FAEE). This is one way of synthesising the fatty acid ester of palm oil that is being researched. Of them, ethanol is less hazardous than methanol and is mostly produced by the fermentation of agricultural products. The previous studies on transesterification process and ester quality using a molar

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ratio of alcohol (ethanol and methanol) to palm oil of 6:1 catalyzed by KOH and NaOH at 1%w showed that the PEE yield was close to the PME yield, because the transesterification process for PEE and PME production was set at the same parameters, such as molar ratio of alcohol to palm oil, catalyst quality, and reaction time and temperature. The mean yield of PEE and PME was between 97.02 and 99.64%w [6, 7]. Nevertheless, the NaOH and KOH catalysts resulted in a high amount of water and free fatty acid. They led to soap formation to a certain extent by hydrolysis of the triglycerides, which reduced the ester content and added water pollution [17]. The group of ethoxide catalysts, particularly potassium ethoxide ($KOCH_2CH_3$), did not generate moisture in the process of catalyst preparation. As a result, the soap and triglycerides were dropped, leading to a higher ester yield than the use of NaOH and KOH catalysts. Moreover, the PEE catalyzed by $KOCH_2CH_3$ led to an ester yield of more than 99% [17, 18]. The physical characteristics of PEE (made from palm olein, free-water ethanol, and potassium ethoxide) and diesel-PEE blends (diesel mixed with PEE from 10 to 50% v/v) in comparison to ordinary diesel are thus the focus of the research project. To inspect performance and emission characteristics, the prepared fuels were operated at a constant speed of 3,000 rpm in a HSDI diesel engine generator under various power generation scenarios.

II. LITERATURE REVIEW

The earlier studies on PEE preparation were started by the transesterification between palm kernel oil, hydrated ethanol (95% purity), and KOH catalyst by using the alcohol/oil molar ratio at 5:1 and 1% KOH at reaction conditions of 60 °C temperature and 120 min duration, resulting in a PEE yield of 96% [19]. The molar ratio of hydrated ethanol to crude palm oil at 9:1, catalyzed by 1% KOH at 60 °C temperature and 120 min duration, led to PEE yield at 90% [20]. The changes of the molar ratio of ethanol to palm oil from 6:1 to 12:1 catalyzed by KOH and sodium salts at reaction temperature lower than 60 °C and 120 min duration caused PEE yield at 75% [21, 22]. To enhance the yield, the FAEE prepared from palm olein was examined. This is due to the palm olein fraction having a higher number of long-chain and unsaturated fatty acids than the stearin oil. Therefore, the improved yield of FAEE was higher for ester content than for the unrefined palm and palm kernel oils. Additionally, anhydrous ethanol (99.9% purity) applied with catalysts resulted in recovering FAEE yield [23]. A key parameter affecting the highest ester yield depends on the option of catalysts. PEE produced by palm olein, moisture-free ethanol and KOH gave the ester content more than 96% [4], but it required large quantities of reactants and a delayed reaction time. The PEE catalysed by potassium methoxide (KCH_3O) resulted in a yield of up to 98% [23, 24]. However, the KCH_3O is at a cost, and a certain amount of water from the transesterification process causes soap formation. Besides, the raw materials must be refined to a certain quality as they react under both catalysts. NaOH is an alternative catalyst that is superior to both catalysts in terms of cost and alcohol/oil molar ratio optimization. The ester yield was more than 97% [6, 11, 25]. Moreover, there was the study of choline hydroxide in producing PEE, but the PEE yield was by 90% [26]. Nevertheless, the hydroxide and methoxide catalysts resulted in a high amount of water and free fatty acid. They led to soap formation to a certain extent by hydrolysis of the triglycerides, which reduced the ester content and added the water pollution. The group of ethoxide catalysts, particularly $KOCH_2CH_3$, did not generate moisture in the process of catalyst preparation. As a result, the soap and triglycerides were dropped, leading to a higher ester yield than the use of hydroxide and methoxide catalysts. The yield of PEE catalyzed by $KOCH_2CH_3$ was at 99% [17, 18], and it was similar to the results of [6, 7] studying PEE catalyzed by KOH and NaOH.

The comparative properties of PEE under the catalysts: NaOH, KCH_3O, and KOH were shown they be similar in ester yield and fuel properties by using the alcohol/oil molar ratio at 6:1 under 1% catalysts [2, 6, 7, 23, 25]. For examining fuel properties, PEE was outstanding in physical properties compared with PME reported in [6, 7] by using the same conditions, the alcohol/palm oil molar ratio at 6:1 produced by 1% catalysts (NaOH and KOH) at a reaction temperature of 60 °C and 60 min duration. In cases of engine performance test over the speed range of 1,600 to 2,200 rpm at full load, the use of PEE [12, 25] compared with PME [27] that used the same NaOH catalyst has shown that the trend of BSFC from using PEE was lower than that of PME. PEE catalyzed by KCH_3O [23, 24] compared with PME prepared by KOH [28, 29] has been found to differ in different ester yield, but physical properties were comparable to PME. The comparative analysis of engine performance fueled with PEE and PME by using the same conditions, the alcohol/oil molar ratio at 6:1 prepared by 1% catalysts (NaOH and KOH), indicates that the engine performance using PEE was similar to that of PME. The reduction of exhaust emissions by using PEE was better than PME [6, 7]. The engine characteristics from using PEE showed the change of engine performance compared with diesel, but it was improved by using the diesel-PEE blend. Significantly, the engine performance of the diesel-PEE blends was identical to that of the diesel-PME blends [6, 7]. When compared to diesel, the usage of PEE and PME resulted in lower CO, BS, and PM emissions when monitoring exhaust emissions. Outstandingly, the levels of nitric oxide (NO) from using PEE were lower than those from PME [6, 7]. In summary, the PEE prepared by earlier studies is generally produced from catalysts in terms of hydroxide and methoxide (NaOH and KOH), causing greater soap formation and triglycerides, leading to groundwater pollution. The PEE catalyzed by ethoxide ($KOCH_2CH_3$) has a higher ester yield and lower soap formation than PEE produced by hydroxide and methoxide [1, 6, 7, 17, 23, 25]. The studies of fuel properties and engine characteristics are mainly tested by using PEE and PME catalyzed by KOH and NaOH [13–32], and the engine tests are done in low- and medium-speed engines under various loads [23–32]. The studies of HSDI diesel engines fueled with PEE catalyzed by $KOCH_2CH_3$ have to be further carried out to improve PEE properties and to reduce crude oil consumption and outdoor air pollution. Thus, the experimental investigation of fuel properties and engine characteristics from using PEE catalyzed by $KOCH_2CH_3$ is compared with regular diesel.

III. MATERIALS AND METHODS

A. PEE Production and Blended Fuel Preparation

The following procedures were used to prepare PEE, as referred to in with [6, 7, 17]: transesterification of palm olein and anhydrous ethanol (99.9% w/w). First, the palm olein was heated up at 120 °C for 30 min to remove moisture. Subsequently, the treated palm olein was subjected to a 6:1 molar ratio reaction with 7 g of $KOCH_2CH_3$ mixed with 217.38 g of water-free ethanol in a round-bottom flask with a mechanical stirrer at 60 °C for 60 min, shown in Fig. 1. The PEE and glycerin would be separated by using a separation funnel. The separated PEE would be more than 95% if the separation took 3 to 4 h. In order to eliminate the dissolved glycerin from the separated PEE, 10% HCl was added. The water was used to wash the PEE to guarantee that the catalyst was gone. To eliminate water, PEE was finally heated to 120 °C for 20 min. PEE and glycerol were separated using a separating funnel, as indicated in Fig. 1. The ester yield was tested by gas chromatography, referenced in EN14103. The mean yield of PEE catalyzed by $KOCH_2CH_3$ was at 99.15% w/w. Importantly, this study found that the mean yield of PEE catalyzed by $KOCH_2CH_3$ was more than the mean PEE yields from [6, 7, 24] by using the same conditions (the alcohol/oil molar ratio at 6:1 and 1% catalysts) with NaOH, KCH_3O, or KOH. Following the completion of PEE production, Table 1 displays the physical characteristics of neat PEE (PEE100). According to [6, 7, 24], experiments were conducted using several ASTM methods to determine the fuel density (FD) at 15 °C, Kinematic Viscosity (KV) at 40 °C, Pour Point Temperature (PPT), Cloud Point Temperature (CPT), Flash Point Temperature (FPT), and Calorific Value (CV). These results of PEE100 were within FAME requirements as published by the Department of Energy Business in Thailand (DEBT) [6], except its viscosity was higher than FAME specifications. Additionally, this work compared the physical properties of neat PEE catalyzed by $KOCH_2CH_3$ with those of neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [6, 7, 24]. The physical properties of neat PEE catalyzed by $KOCH_2CH_3$ were similar to those of PEE catalyzed by NaOH, KCH_3O, and KOH. Then, this study compared the physical properties of PEE100 with regular diesel, which was pure diesel (D100) and bought from the petroleum companies. When compared to the specifications of commercial diesel, the physical properties of D100 were within the Diesel specifications as announced by the DEBT [6]. The PPT, CPT, FPT, FD, and KV increased by 11.50 °C, 5.00 °C, 129.71 °C, 3.96%, and 89.59%, respectively, whereas the CV decreased by 11.56% in PEE100 instances compared to D100. Outstandingly, this work has found that the FPT, FD, KV, and CV of PEE100 were higher than those of neat PME catalyzed by NaOH (PME100) studied by [6].

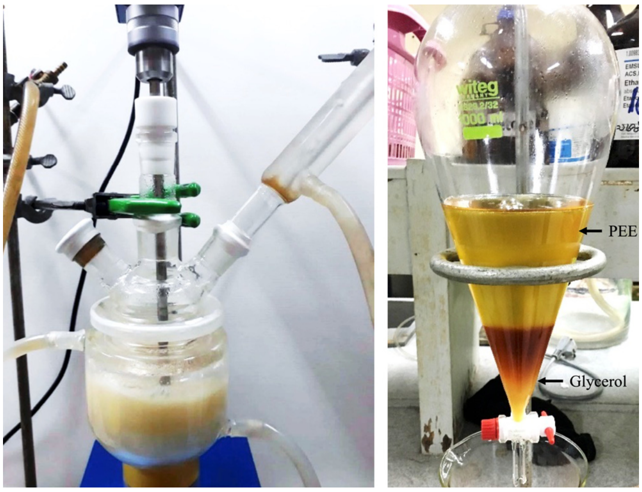

Fig. 1. Preparation of PEE.

Table 1. Physical properties of fuels

Items	Diesel (%v)	Esters (%v)	Price per liter (USD)	PPT (°C)	CPT (°C)	FPT (°C)	FD (kg/m^3)	KV (mm^2/s)	CV (MJ/kg)
ASTM methods	-	-	-	D97	D2500	D93	D1298	D445	D240
Diesel specifications [6]	100	-	-	≤10	-	≥52	<870	<4.10	-
FAME specifications [6]	-	100	-	-	-	≥120	<900	<5.00	-
D100	100	-	1.475	-7.50	7.60	44.98	838.00	3.17	45.17
PEE10	90	10 (PEE)	1.470	-0.75	8.45	81.34	843.70	3.95	44.29
PEE20	80	20 (PEE)	1.466	0.50	8.70	84.49	846.10	4.13	43.16
PEE30	70	30 (PEE)	1.461	1.38	9.45	89.06	849.30	4.40	42.08
PEE40	60	40 (PEE)	1.447	2.05	10.10	97.59	853.40	4.51	41.23
PEE50	50	50 (PEE)	1.452	2.75	11.00	110.40	857.70	4.58	40.41
PEE100	-	100 (PEE)	1.429	4.00	12.60	174.69	871.20	6.01	39.95
PME100 [6]	-	100 (PME)	1.160	6.40	16.20	170.40	870.00	5.84	39.88
PME10 [6]	90	10 (PME)	0.974	-4.60	9.00	79.90	841.00	3.94	44.54
PME20 [6]	80	20 (PME)	0.987	1.30	9.90	84.60	848.00	4.11	43.46

Note: Currency exchange rate: USD 1 = THB 33.79

After the verification of PEE100 properties was complete, the diesel and PEE were combined to create PEE10, PEE20, PEE30, PEE40, and PEE50, respectively. The diesel was mixed at 90, 80, 70, 60, and 50% by volume, while the PEE was mixed at 10, 20, 30, 40, and 50% by volume. All mixtures were produced within the round-bottom glass connected with the mechanical stirrer at a stirring rate of 800 rpm. The blending temperature was fixed at 40 °C [6, 7, 24]. Following completion, the diesel-PEE blends were examined for fuel qualities using a variety of ASTM processes in order to compare them to both diesel and PEE100, as shown in Table 1. According to the property study of diesel mixed with PEE from 10 to 50% v/v, the PPT, CPT, FPT, FD, and KV increased from 6.75 to 10.25 °C, 0.85 to 3.4 °C, 36.36 to 65.42 °C, 0.68 to 2.35%, and 24.61 to 44.48%, respectively, in comparison to diesel. However, the CV decreased from 1.95 to 10.54%. This work compared physical properties of various proportions of diesel mixed with PEE catalyzed by $KOCH_2CH_3$ with those of diesel blended with PEE catalyzed by NaOH, KCH_3O, and KOH in [6, 7, 24, 25]. The results of physical properties in this work were in line with the results of [6, 7, 24, 25]. In terms of diesel-PEE blends compared with diesel-PME blends [6], this study focuses on diesel blended with different palm esters at 10% and 20 % because they are currently potential alternative fuels to diesel in Thailand. Outstandingly, the physical properties of PEE10 and PEE20 were similar to those of PME10 and PME20, except that the PPT of PEE10 and PEE20 was lower than that of PME10 and PME20 (Table 1). In addition, the Department of Energy Business's published diesel standards are compared with the PEE10 attributes in [2]. The PEE10 for FPT was higher than this specification, yet the FD and KV readings fell within the parameters of ordinary diesel. To assess the economic feasibility of PEE production and its scalability for widespread adoption, there was a cost analysis of neat PEE and its blends compared to the price per liter of commercial fuels using in Thailand, such as regular diesel (D100), neat PME (PME100), PME10 (diesel mixed with 10%PME), and PME20 (diesel mixed with 20%PME). The cost analysis was referred from the literature [2], and the results of the price per liter were shown in Table 1. The cost of PEE100 was higher than that of PME100, increased by 23.18%. This is because the price of the $KOCH_2CH_3$ catalyst was higher than that of the NaOH catalyst. However, the cost of PEE100 was slightly lower than that of D100, reduced by 3.24%. This is because the price of neat diesel bought from the petroleum companies was higher. Currently, PME10 and PME20 are used as an alternative fuel in Thailand in various industrial sectors. The physical properties of PEE10 and PEE20 were similar to those of PME10 and PME20, but the cost of PEE10 and PEE20 was higher than that of PME10 and PME20, increased by 50.97% and 48.55%, respectively. However, because neat PEE was less expensive than neat diesel, the cost of diesel-PEE blended fuel dropped as PEE increased.

B. Experimental Investigation of HSDI Diesel Engine

The schematic diagram of the experimental setup is studied from [2, 6, 7] and indicated in Fig. 2. A HSDI diesel engine (Model: Mitsuki: MIT-186FG; cylinder, 1 cyl; capacity, 0.406 L; power (max.), 8.5 kW @ 3,000 rpm; compression ratio, 17.5:1) coupled to a generator that can generate up to 5 kW at 3,000 rpm is used to study the fuels. Electrical loads were adjusted to add the electrical power generated from several bulbs. The electrical power was measured using a digital multi-function power meter connected to the current transformer and a hardlock for the RP series attached to a USB converter for computer processing. Air intake, coolant, and exhaust gas temperatures were recorded by using the K-type thermocouples connecting to a temperature data logger (Agilent, Model 34970A Data acquisition), which was displayed on a computer. An air flow meter and a venturi tube were used to measure the air flow rate. In order to record the fuel consumption rate, this work also included a gasoline cylinder that connected to a load cell sensor and an Arduino for processing on an LCD display. A speed sensor that connected to the Arduino for processing on an LCD display was used to record the engine speed. The USB converter changed both parameters so they could be seen on the computer. In the exhaust gas investigation, the NO, UHC, CO, and BS levels were measured by a Cosber: KWQ-5 emission analyzer and a Cosber: KYD-6 opacimeter.

The experimental procedures of the HSDI diesel engine were tested under 100 h. Engine performance and exhaust emissions were measured more than 5 times, studied from [2, 6, 7]. The testing procedures were as follows: first, D100 was used to warm up the engine for 15 min. To begin the experiments, the engine speed was set to 3,000±50 rpm. The fins, surrounding air, and air intake manifold were all measured to be 30±5 and 80±10 ºC, respectively. The initial load was applied at 20% after the engine had steadied. In order to measure the period of gasoline use and calculate the fuel consumption rate, the fuel mass was kept constant at 17g. Measurements were also made on engine parameters such as electrical power, air flow rate, temperature, and exhaust pollutants. After completing the 20% electrical load, the electrical load was raised to 40%, 60%, 80%, and 100%, in that order. The parameters mentioned in the experiment at 20% load were recorded during the analysis of each load, which prompted the investigation of changes in engine performance. The diesel-PEE blends and PEE100 were inspected starting with PEE10, PEE20, PEE30, PEE40, PEE50, and PEE100, respectively, after the engine running with D100 was completed. They were tested in identical conditions as D100. The engine speed was controlled at 3,000±50 rpm with load fluctuation, and to examine the shift in engine characteristics, engine parameters were noted. Finally, all metrics from the diesel-PEE blends and PEE100 were compared to D100 to determine the change in the engines' performance and emissions.

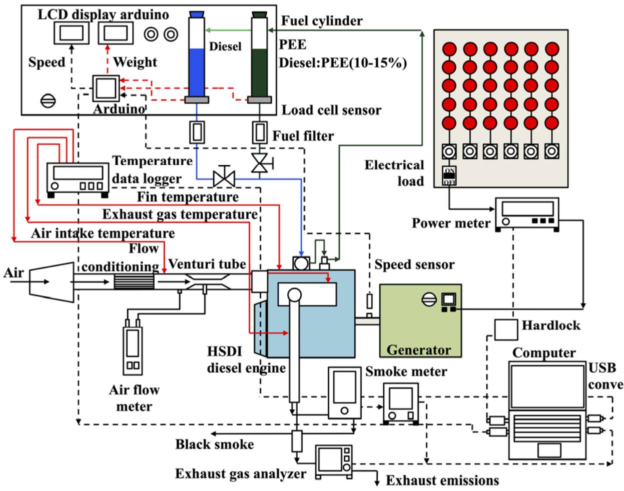

Fig. 2. Schematic diagram of experimental setup.

IV. RESULT AND DISCUSSION

The prepared fuels were studied with an HSDI diesel engine connected to a generator to generate electrical power according to different loads. The engine test was operated at 3,000 rpm and various electrical loads. The electrical load was added by the various bulbs, which were converted into the electrical power produced by each load. In order to generate electrical power at 0.93±0.002, 1.92±0.003, 2.83±0.002, 3.65±0.003, and 4.45±0.004 kW, respectively, this study modified the electrical load from the lights at 20, 40, 60, 80, and 100% of the electrical load. The accuracy of power measurement did not exceed ±0.004 kW. Similarly, the overall uncertainty of experimental performance and emission parameters was based on ±1.93%, as studied from

[32]. They caused a change in engine characteristics, as mentioned below:

A. Brake Specific Fuel Consumption

In cases of engine performance, Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) are used to find the optimum conditions of engine operation, since they assess the engine's energy transformation and identify the optimization of fuel consumption and emissions [8-14]. BSFC is computed by dividing input energy by Electrical Power (EP), as shown in Fig. 3. The addition of EP resulted in a constant decrease in BSFC, with the lowest BSFC happening at 3.65 kW of EP since the EP rose more than the fuel usage [2]. The BSFC was then increased until the EP reached 4.45 kW due to the increase in fuel injection being more than the EP produced in that situation to maintain the level of mechanical losses [24]. The optimum BSFC was found at 3.65 kW of EP because of the lowest BSFC.

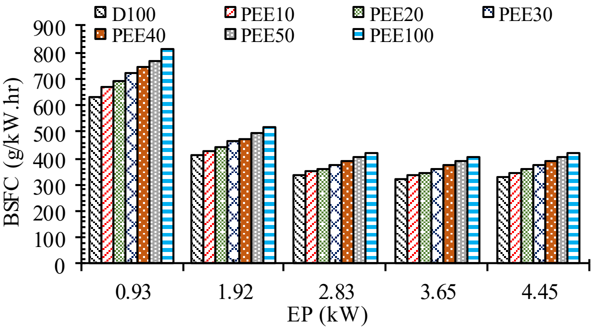

Fig. 3. BSFC with increasing electrical power.

Overall, the use of neat PEE and its blends caused a continuous addition of BSFC in each electrical power. At 3.65 kW of EP, the use of PEE100 resulted in the addition of BSFC at 23.97% as compared with D100. This result was consistent with the results of [6, 7, 11, 24], as described by the neat PEE, which had higher viscosity and density than D100 (Table 1), causing the fuel injection timing to be more advanced, resulting in an increased fuel injection rate [8–10]. Moreover, the escalation of fuel injection rate from running at the same power resulted in the addition of BSFC due to the CV of neat PEE being lower than that of D100 [6, 7]. However, BSFC reduction can be improved by blending diesel. This is because the increasing proportion of diesel leads to improvements in density, viscosity, and CV [6, 7, 11, 24]. As a result, the regular diesel mixed with PEE from 10 to 50% led to the addition of BSFC from 3.25 to 20.05%, respectively. These results were in line with [6, 7, 11, 24], because the density and viscosity decreased and CV increased with increasing diesel content (Table 1). The novelty of this study shows that the use of neat PEE catalyzed by $KOCH_2CH_3$ increased the BSFC by only 23.97%, as compared to the neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [6, 7, 24, 25] which had a BSFC of more than 26.86%. The use of neat PEE catalyzed by $KOCH_2CH_3$ and diesel-PEE blends was similar to BSFC to PME catalyzed by NaOH and KOH and diesel-PME blends in the results of [6, 7]. Importantly, the use of PEE10 and PEE20 had BSFC only increased by 3.24% and 6.90% compared to D100, and they were similar to the results of PME10 and PME20.

B. Brake Thermal Efficiency

BTE is calculated as the output electricity produced per unit of input energy contained in fuels, which is dependent on the fuel flow rate and CV according to engine tests [2, 6, 7, 20], as illustrated in Fig. 4. As EP climbed, so did BTE, with 3.65 kW of EP yielding the maximum BTE because this engine's input energy was appropriately transformed into electrical power. Nonetheless, the engine test at 4.45 kW of EP shows that the BTE was reduced due to increased engine energy losses while operating at full power [2, 6, 7, 24]. As a result, the best BTE of this study was at 3.65 kW of EP. Therefore, the optimum engine performance was found at 3.65 kW of EP due to the lowest BSFC and the highest BTE, while this condition was used to describe the effects of various exhaust emissions.

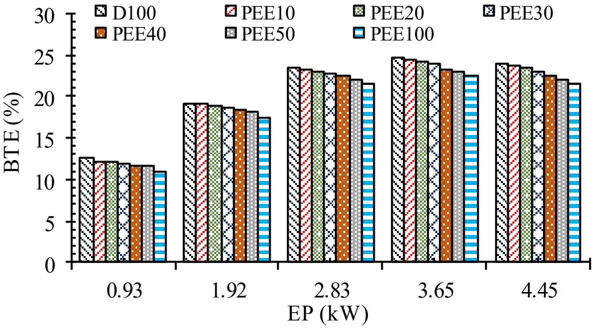

Fig. 4. BTE with increasing electrical power.

In each electrical power, the use of neat PEE and its blends caused a continuous abatement of BTE compared to D100. At 3.65 kW of EP, the use of PEE100 operated for this engine resulted in the reduction of BTE at 8.80%. This result was consistent with the results of [6, 7], because the CV of PEE100 was lower than that of D100 (Table 1). When examined at the same power, it was found that the fuel consumption rate increased due to the increase in density and viscosity and the decrease in CV to maintain the same power level, resulting in a decrease in BTE. However, the improvement of BTE can be achieved by mixing regular diesel with PEE [8-14]. As a result, the regular diesel mixed with PEE from 10 to 50% led to only a slight lessening of BTE from 1.22 to 7.28%, respectively. These results were similar to the results of [6, 7, 11, 24], which investigated the diesel blended with PEE catalyzed by NaOH, KCH_3O, and KOH. BTE was improved due to the reduction of density and the addition of CV according to the amount of diesel added (Table 1). As examined at the same power, fuel flow rate was improved continuously according to the amount of diesel added. Outstandingly, this work has found that the use of neat PEE catalyzed by $KOCH_2CH_3$ was a higher BTE than the neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [6, 7, 24, 25] which had a lower BTE than 10.74%. Moreover, the use of neat PEE catalyzed by $KOCH_2CH_3$ and diesel-PEE blends was similar to BTE to PME catalyzed by NaOH and KOH and diesel-PME blends in the results of [6, 7]. Importantly, the use of PEE10 and PEE20 had BTE only decreased by 1.22% and 2.09% compared to D100, and they were similar to the results of PME10 and PME20.

C. UHC Emission

The major components of PM formation include UHC, CO, and BS emissions [2]. The use of neat PEE and its blends leads to the following changes in these pollutants. First, UHC formation mainly occurs from incomplete combustion in the fuel-rich zone of non-premixed combustion [8–10]. Fig. 5 shows that the levels of UHC were reduced with increasing EP, and the lowest release of UHC was found at 3.65 kW of EP, which was consistent with the trend of BTE and BSFC. The UHC emission highly increased at 4.45 kW of EP, since the main fuel injection occurred more at full power. As a result, a hogher fuel density was accumulated within the non-premixed burning zone, and then the UHC concentration was highly raised via exhaust valve opening [8–10].

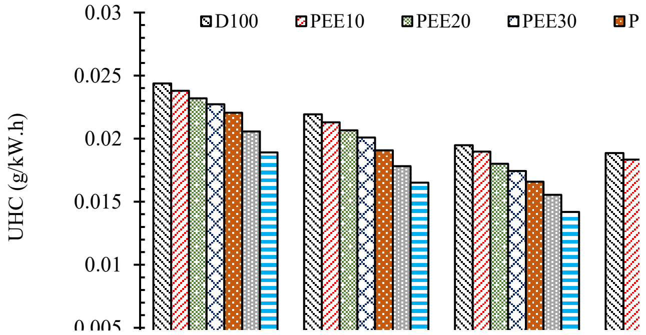

Fig. 5. UHC with increasing electrical power.

Outstandingly, the use of neat PEE and its blends caused a continuous dwindling of UHC in each electrical power. At 3.65 kW of EP, the use of neat PEE indicates that the UHC emission declined by 30.42% compared to D100. It is explained by the PEE, which consisted of 73.5% carbon, 12.7% hydrogen, and 13.8 % oxygen (by mass), resulting in a reduction of fuel-rich combustion and rapid flame quenching due to more thorough burning in the diffusive zone [13, 14]. In addition, the neat PEE had a higher density and viscosity than D100, leading to the addition of more fuel injection and oxygen content in combustion zones. Especially, the complete combustion in the diffusive zone was increased, resulting in the reduction of UHC emission [8–10]. Similarly, the mixtures of diesel and PEE added from 10 to 50% identified the reduction of UHC in the range of 2.70 to 20.61% compared with diesel. They were in line with [13, 14], due to the oxygen element of PEE varying in the proportion of diesel-PEE blended fuels. This study shows that the use of neat PEE catalyzed by $KOCH_2CH_3$ was able to reduce UHC emission by 30.42%. Moreover, the use of PEE catalyzed by $KOCH_2CH_3$ and diesel-PEE blends was similar UHC emission to the PME catalyzed by NaOH and KOH and the diesel-PME blends in the results of [25, 27]. Because the carbon-hydrogen-oxygen concentration of PEE catalyzed by $KOCH_2CH_3$ was similar to that of PME, the PME was composed of 74.5% carbon, 12.5% hydrogen, and 13.0% oxygen (by mass) as reported by [28]. Importantly, the use of PEE10 and PEE20 decreased UHC by 2.70% and 8.09% compared to D100, and they were similar to the results of PME10 and PME20.

D. CO Emission

CO is the origin of black carbon formed by the fuel-rich combustion, reported in Fig. 6. The CO levels were reduced with increasing EP, and the lowest CO release was found at 3.65 kW of EP, which was in line with the trend of BTE and BSFC. The CO emission increased at 4.45 kW of EP due to the changes in the air-fuel ratio at a constant speed. The fuel-rich combustion was increased, and more CO was released [2, 6, 7]. Importantly, the use of neat PEE and its blends led to the continuous reduction of CO in each electrical power. The verification of 3.65 kW of EP by comparing with D100 identifies that the neat PEE resulted in a decrease of CO at 48.53%. Likewise, the blending of diesel with PEE from 10 to 50% led to the abatement of CO from 10.76 to 37.87%. These results were similar to the results of [33], because the neat PEE had more density and viscosity than diesel, resulting in more oxygen elements. CO emissions were lowered as a result of increased full combustion in combustion zones.

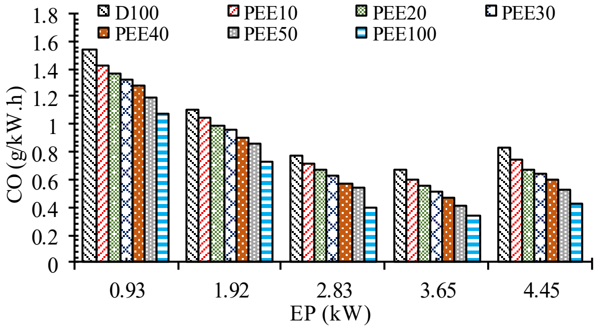

Fig. 6. CO with increasing electrical power.

Besides, the CO emission from these results was identical to that from PEE catalyzed by NaOH, KCH_3O, and KOH and their blends [6, 7, 24]. They were explained by the chemical formula of neat PEE catalyzed by $KOCH_2CH_3$, which consisted of carbon-hydrogen-oxygen concentration, while oxygen content resulted in a more thorough burning during the diffusion combustion phase, leading to the reduction of CO emission. In cases of diesel-PEE blends, replacing diesel with PEE by mixing resulted in a reduction in oxygen content. This resulted in a slight decrease in CO emissions as the diesel proportion increased. The novelty of this study indicates that the use of neat PEE catalyzed by $KOCH_2CH_3$ was able to reduce CO emission by 48.53% which was more than the use of neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [6, 7, 24, 25], decreased by only 28%. Similarly, the results of diesel-PEE blends and PEE catalyzed by $KOCH_2CH_3$ were the same as those of [6, 7] comparing PME and its mixtures with diesel. The CO release was dropped with the addition of PME. Outstandingly, the CO release from using PEE catalyzed by $KOCH_2CH_3$ was lower than that of PME studied by [6, 7], since the carbon element in PEEs' molecular formula ($C_{6.13}H_{12.70}O_{0.86}$) was less than that in PMEs' chemical structure ($C_{6.21}H_{12.50}O_{0.81}$), as explained in the UHC section. Importantly, the use of PEE10 and PEE20 decreased UHC by 10.76% and 15.94% compared to D100, and they were similar to the results of PME10 and PME20.

E. BS Emission

To examine the relationship between BS and PM, the BS is basically released from incomplete combustion within the diffusive combustion phase to form the PM, shown in Fig. 7. The BS emission was increased with increasing EP, because the continuous addition of fuel consumption corresponded to the continuous escalation of EP. Consequently, the non-premixed combustion zone's primary fuel injection was increased, which led to a steady rise in BS emissions [2]. However, the optimum engine performance was found at 3.65 kW of EP, showing that the BS emission was raised by only 12% of black-smoke opacity. Eminently, the use of neat PEE and its blends resulted in the continuous reduction of BS emission in each EP. When comparing neat PEE to diesel, the BS emission decreased by 36.04%. The use of diesel mixed with PEE from 10 to 50% decreased the BS levels from 5.56 to 27.41%. These results were similar to those reported by [9, 10, 23, 24] studying the PEE catalyzed by NaOH, KCH_3O, and KOH and their blends. This is because the oxygen concentration in the neat PEE increased with increasing fuel injection, which was influenced by its viscosity and density. As a result, the diffusive zone had more complete combustion, and it was better than the combustion of pure diesel (carbon-hydrogen concentration).

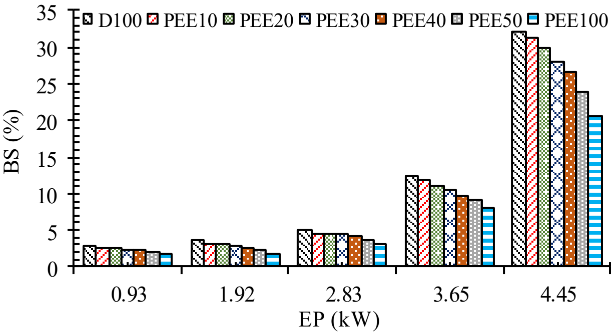

Fig. 7. BS with increasing electrical power

Likewise, adding diesel to the PEE mixture led to a decrease in oxygen content, resulting in a reduction of BS as the proportion of diesel increased. Besides, the trends of BS reduction from neat PEE and its blends were consistent with those from neat PME and its mixtures reported by [25–29]. This study shows that the use of neat PEE catalyzed by $KOCH_2CH_3$ was able to reduce BS emission by 36.04% which was more than the use of neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [23–25], decreased by only 35%. Moreover, the use of PEE10 and PEE20 decreased BS emission by 5.56% and 12.09% compared to D100, and they were similar to the results of PME10 and PME20.

F. PM Emission

Fig. 8 indicates that the PM is determined by multiplying the exhaust gas volume flow rate by the correlation value, which is based on the proportion of BS according to the EP [2]. The PM emission was added with increasing EP, and they were in line with the results of the BS emission in the previous section due to the main fuel injection increased in the diffusive combustion zone [2]. Nevertheless, the use of neat PEE and its blends led to a continuous decrease in PM emission in each EP. In terms of neat PEE, the PM emission was relieved by 44.58% compared with diesel. The use of diesel mixed with PEE from 10 to 50% dropped the PM levels from 6.21 to 34.56%. These results corresponded to the results of BS emission. This is because there was an increase in oxygen content, which was influenced by adding viscosity and density according to PEE. As a result, the complete combustion in non-premixed zone was raised with increasing PEE, resulting in the continuous dwindling of PM emission [2, 6, 7]. The novelty of this study indicates that the use of neat PEE catalyzed by $KOCH_2CH_3$ reduced PM emission by 48.58% which was more than the use of neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [6, 7, 24, 25], decreased by only 43%. The PM results obtained from this work were comparable to those obtained from [6, 7], which examined the PM emission of neat PME and diesel-PME mixes catalyzed by NaOH and KOH. The PM levels reduced with increasing PME. Outstandingly, the letdown of PM from using PEE catalyzed by $KOCH_2CH_3$ was higher than the use of PME of [6, 7] due to the lessening of carbon atoms in the chemical formula of neat PEE resulting in the decrease of black carbon formed by UHC, CO, and BS emissions. Moreover, the use of PEE10 and PEE20 reduced PM emission by 6.21% and 14.31% compared to D100, and they decreased more than the results of PME10 and PME20 in literature [6, 7].

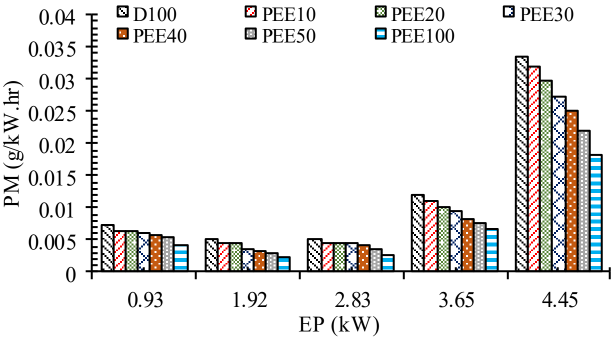

Fig. 8. PM with increasing electrical power

G. NO Emission

Nitrogen oxides are another important pollutant emitted by diesel engines that must be monitored. When nitrogen oxides are produced at high temperatures and with a higher concentration of O_2, they are commonly referred to as nitric oxide (NO), leading to a dangerous contributor to climate change [6, 7, 9, 23, 24]. Fig. 9 shows that the NO levels were increased with increasing EP; he high flame temperature is caused by the increased oxygen element from having a fast engine speed. leading to a continuous addition of NO emission according to the increase in EP [2].

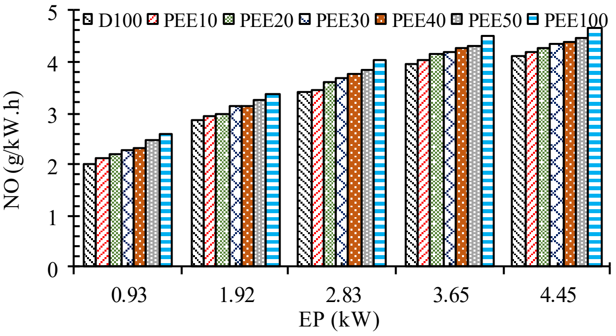

Fig. 9. NO with increasing electrical power.

The use of neat PEE and its blends caused a continuous escalation of NO emissions in each EP. As compared to diesel at 3.65 kW of EP, the neat PEE led to an increase in NO emission to 13.81% and the level of NO increased from 2.18 to 9.04% by using diesel blended with PEE from 10 to 50%. These results had the same NO release as the results of [6, 7, 24], which investigated the PEE catalyzed by NaOH, KCH_3O, and KOH and their blends. According to the description, the use of neat PEE increased the oxygen concentration, which in turn caused the combustion to be more complete within the rapid combustion zone. The flame temperature was increased within this zone, causing the high NO formation. Furthermore, the adjunct oxygen content that is initiated from itself might prolong the burning duration in the premixed zone, resulting in more time for NO formation [9, 10, 13, 14]. Similarly, the neat PEE had a higher density and viscosity than diesel, resulting in increased combustion chamber pressure and advanced injection timing. As a result, more fuel injection was added in combustion zones, leading to an increase in oxygen content and flame temperature [33]. To decrease the NO formation, the use of diesel-PEE blends was considered, because adding diesel to PEE blend resulted in a decrease in oxygen concentration, resulting in a decrease in flame temperature and NO formation, as the diesel proportion increased._The novelty of this work found that the use of neat PEE catalyzed by $KOCH_2CH_3$ increased NO emission by 13.81% which was less than the use of neat PEE catalyzed by NaOH, KCH_3O, and KOH in the literature [6, 7, 24], increased by up to 22%. Moreover, the results of this work were compared with the results of [6, 7] examining PME and its blends. NO emission was increased with increasing PME, while they were within the scope of Euro 3 as well. Eminently, the PEE catalyzed by $KOCH_2CH_3$ had lower NO emissions than PME produced by [6, 7] due to the low flame temperature in combustion zones. Importantly, the use of PEE10 and PEE20 increased NO emission by 2.18% and 4.35% compared to D100, and they decreased more than the results of PME10 and PME20 in the literature [6, 7]. Among other things, this study shows that the use of neat PEE led to an increase in NO release. To mitigate NO emissions and reduce environmental impacts, this study used a diesel-PEE blend, which indicated PEE10 increased NO emissions by only 2%. However, there are other options to reduce NO emissions, such as preheating PEE, blending alcohols, using exhaust gas recirculation (EGR), etc., as referenced in [1, 2, 4, 9, 10].

V. CONCLUSION

The experimentation of PEE catalyzed by $KOCH_2CH_3$, diesel-PEE blends, and regular diesel fuel for an HSDI diesel engine shows the optimum engine performance at 3.65 kW. The use of fuels can be concluded as follows:

In the first case, the comparative fuel properties and engine characteristics between neat PEE and regular diesel indicate that the neat PEE has a higher fuel density and viscosity and a lower energy value. These results led to a decrease in BTE of 9% and an increase in BSFC of 24%. Nevertheless, the advantage of operating neat PEE for this engine shows that there was the abatement of UHC, CO, BS, and PM emissions, which dropped by 30%, 49%, 36%, and 45%, respectively. The NO emission was increased by 14%. Thus, the use of neat PEE results in greater reductions in black carbon and PM with only minimal NO emission.

The addition of diesel mixed with PEE reports that there were improvements in fuel properties, especially fuel density, viscosity, and heating value. They led to the increase of BTE and the decrease of BSFC and NO emissions better than the use of neat PEE. However, the use of the diesel/PEE volume ratio at 50:50 led to a decrease in BTH by 7% and an increase in BSFC and NO by 20% and 9%, respectively. This research suggests the use of a diesel/PEE volume ratio of 90:10 due to the slight changes in BTE, BSFC, and NO. The releases of UHC, CO, BS, and PM were reduced by 3%, 11%, 6%, and 6%, respectively.

Finally, the future studies will examine how HSDI diesel engines' performance and wear are affected by long-term testing with PEE10 and neat PEE in comparison to diesel. Moreover, the studies of fuel properties and engine performance parameters, and exhaust emissions from preheating PEE and using EGR were also conducted to investigate the reduction of NO emissions. Furthermore, a research project concerning Life Cycle Assessment (LCA) of PEE at the cradle-to-cradle level would be initiated. This includes (1) raw material extraction, (2) material manufacturing, (3) product manufacture, (4) use, and (5) disposal.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Charoen Chinwanitcharoen is the first author who prepared the fuels, studied the physical properties of fuels, and wrote the abstract, introduction, and materials and methods. Cherdphong Seedao measured the physical properties of fuels. Sathaporn Chuepeng contributed to conceptualization, research design, data analysis, conclusion, recommendation, and writing-review & editing draft. Ekkachai Sutheerasakis the corresponding author who studied the experimental investigations of engine performance and exhaust emissions, analyzed experimental data, and wrote the introduction, materials and methods, and results and discussion; all authors had approved the final version.

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