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RESEARCH ARTICLE

Performance and Emission Characteristics of a High-Speed Diesel Engine Using a 20% Palm Oil Ester and Ethyl Alcohol Blend

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ABSTRACT - The issue of diesel engine exhausts is expanding to affect human health, while oxygenated fuels have been continuously studied for a healthier environment. Palm oil ester (POE) is applied in Thailand to reduce exhaust products, but its viscosity is thicker than diesel fuel, which may cause injection systems. It has been improved by mixing with diesel, and diesel blended with 20% POE (POE20) is surveyed as an alternative fuel to reduce viscosity. Currently, ethyl alcohols combined with this blend have gained a lot of attention due to improved fuel properties and the alleviation of exhaust products. Therefore, this research studies a diesel engine's performance parameters and pollution products at high speed at 3,000 rpm and various powers when operated with POE20 and combinations of POE20, 5% ethyl acetate, and ethyl alcohol up to 20%. The results indicate that the POE20 had lower engine performance but higher carbon dioxide and nitric oxide than regular diesel. The 10% ethyl alcohol blended with POE20 improved the brake thermal efficiency, similar to regular diesel. However, POE20 mixed with ethyl alcohols by more than 10% remarkably changed performance parameters and pollution products compared with regular diesel and POE20.

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1.0 INTRODUCTION

A fuel-efficient and low-maintenance diesel engine is commonly used as a power generator and for various vehicle applications. The exhaust products of diesel engines are causing serious harm to human health and the environment. Particularly, unburned hydrocarbons (UHC), carbon monoxide (CO), and black smoke (BS) have created particulate matter (PM) of various sizes, such as PM2.5 and PM10. Most combustion processes of petroleum-derived diesel, in terms of incomplete combustion of hydrocarbons, have released these products, which lead to the release of innumerable PM [1]. Nitrogen oxides (NO_x), which consist mostly of nitric oxide (NO), are also a serious environmental concern because of their burden in smog formation [2]. Therefore, the various uses of oxygenated additives, especially fatty acid esters (FAEs) and alcohols, are getting attention due to renewable bio-based resources and high oxygen molecules providing the potential to reduce these emissions [3].

FAEs are produced by various plant and waste oils transesterified with ethyl and methyl alcohols via homogeneous catalysts to synthesize the fatty acid ethyl esters (FAEEs) and fatty acid methyl esters (FAMEs) [4]. The prior research [5-9] studied the intensive and extensive properties of FAEs and then the experimental exploration of various parameters of diesel-engine operation. One of the important problems was the extremely high increase in density and viscosity that affected the injection and spray characteristics. In the same way, the calorific value (CV) of FAEs was less than that of common diesel, affecting the diesel engine parameters differently. In cases of tentative investigation of performance values and exhaust products, they were used with the single and multi-cylinders of diesel engines at low and medium revolutions by adjusting brake powers. Remarkably, there was a dwindling of brake thermal efficiency (BTE) and the addition of brake specific fuel consumption (BSFC) when compared with common diesel. Additionally, they mainly created a huge increase in carbon dioxide (CO_2) and NO based on substrates that reacted with alcohol. However, the UHC, CO, and BS drastically decreased due to high oxygen (O_2) atoms in the esters.

To improve the density and viscosity issues, common diesel was mingled with the adjustment of the proportions of FAEs. Different types of oils were reacted with alcohols, and then they became coconut oil methyl ester (COME), fish oil ethyl ester (FOEE), jatropha oil methyl ester (JOME), moringa oil methyl ester (MOME), palm oil ethyl ester (POEE), palm oil methyl ester (POME), safflower oil methyl ester (SOME), waste frying oil ethyl ester (WFEE), and waste frying oil methyl ester (WFME). These esters were used in a wide variety of diesel engines at different speeds and loads, while the overall results were summarized as follows: Firstly, the blend of diesel and FAEs (lower than 10%) was in line with diesel in cases of physical characteristics and BTE. The BSFC was increased by 3%, but the carbon particulates formed from CO and BS releases were dropped by 5%. Next, the diesel mixed with FAEs at 20% led to a slight reduction of BTE, but the releases of carbon particulates were dramatically reduced, although there was a trivial addition of CO_2 and NO emissions [5-18]. Importantly, the diesel mixed with FAEs (30% and above) caused the lessening of BTE by more than 10% and the enlarging of BSFC by more than 15%, depending on the oil type. The CO_2 and NO emissions increased by

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more than 13% [5-7, 9, 12]. Therefore, diesel blended with 20% FAEs is being pushed as a renewable energy source. Table 1 shows the results of some ASTM procedures. Specifically, fuel density (FD) at 15 ºC, kinematic viscosity (KV) at 40 ºC, and lower heating value (LHV) were referenced in the various reports. Besides, there were reports of performance peculiarities (BTE and BSFC) and exhaust products (CO_2, NO, and CO) from using normal diesel blended with 20% FAEs, such as COME, FOEE, JOME, MOME, POEE, POME, SOME, WFEE, and WFME, to make COME20, FOEE20, JOME20, MOME20, POEE20, POME20, SOME20, WFEE20, and WFME20, respectively. They identified the increase of FD and KV and the dwindling of LHV, and then BTE and BSFC were mainly permuted, and CO_2 and NO were enlarged in comparison to ordinary diesel. However, CO emissions decreased [5-18].

Table 1. Results of diesel mixed with 20% FAEs [5-18]

Fuels	Results Compared with Diesel Baseline (%)							
	FD	KV	LHV	BTE	BSFC	CO_2	NO	CO
POEE20	↑2	↑35	↓3	↓2	↑5	↑2	↑6	↓7
POME20	↑1	↑24	↓8	↓4	↑13	-	↑9	↓38
WFEE20	↑1	↑9	↓3	↓1	↑4	↑1	↑3	↓9
WFME20	↑1	↑7	↓3	↓3	↑4	↑1	↑3	↓8
MOME20	↑2	↑14	↓3	↓5	↑9	-	↑12	↓42
POME20	↑1	↑7	↓3	↓4	↑7	-	↑5	↓49
JOME20	↑2	↑12	↓3	↓5	↑8	-	↑7	↓46
SOME20	↑1	↑8	↓4	↓8	↑13	-	↑8	↓38
FOEE20	↑0.3	↑34	↓2	↑4	-	↑1	↓1	↓11
COME20	↑1.4	↑16	↓3	-	↑5	-	-	-

Note: Increase [↑] and Decrease [↓]

For adding other oxygenated fuels in terms of alcohols, some researchers have investigated the physical properties of diesel mixed with alcohols via emulsification. Especially ethyl alcohols (ethanol and ethyl acetate) produced from starch-based crops by fermentation are lower in cost and less toxic than other alcohols, such as butyl, methyl, and propyl alcohols [19-20]. The previous studies [19-25] investigated the fuel properties and the operating behavior of diesel engines using various proportions of diesel and alcohols (ethanol, ethyl acetate, butanol, methanol, propanol, etc.), leading to various results. In the case of physical properties, alcohols could be directly combined with common diesel. However, the diesel-alcohol proportions were limited to the 5-10% range due to a slight decrease in density, viscosity, and CV. They did not affect the diesel-engine operation [3, 19, 21]. However, diesel mixed with alcohols by more than 10% was greatly lower for these properties than diesel standards and faster stratification [22-23]. Diesel fuel could not be mixed with more than 20% alcohol since the stratification time occurred within 24 hours, resulting in a high engine knock and viscosity and density significantly lower than diesel fuel, which expeditiously caused wear and tear on the fuel injection pump [19, 21, 23]. In terms of engine characteristics, the combinations of diesel and alcohol changed the values of BTE and BSFC. Particularly, diesel mixed with butyl alcohols (N-butanol and iso-butanol) by less than 10% had a higher BTE than diesel baseline and its combination with ethyl alcohols for the same mixture proportion because the CV of butyl alcohols was higher than that of ethyl alcohols and other alcohols [19-20]. Nevertheless, diesel blended with ethyl alcohols resulted in better combustion characteristics and lower engine wear than diesel mixed with other alcohols [24-25]. Importantly, the releases of UHC, CO, and NO by mixing ethyl alcohols were lower [19-22].

The most important problem with diesel mingled with alcohols is its quick stratification and low viscosity compared to diesel. Several studies have improved the fuel properties of diesel blended with alcohols by adding FAEs, followed by studies of diesel engine layouts under adjusting conditions. For improving the fuel blends, the mixtures of diesel, FAEs, and alcohols are emulsified and well homogeneous depending on the proportion and purity of the alcohols used. These blends can improve physical properties close to the diesel baseline [22-23]. The earlier inquisitions on emulsification between diesel and both additives mainly used ethanol and FAMEs, such as POME, JOME, WFME, etc. For monitoring the power, efficiency, combustion, and durability of diesel engines, they were altered in proportions to diesel, FAMEs, and ethanol [22]. For measuring various exhaust gases, the blends of diesel, FAMEs, and ethanol released lower CO, CO_2, and BS up to 40%, but the solubility of fuel blends depended on the mixing temperature and the ethanol purity [23]. The addition of anhydrous ethanol (99.5% purity) led to better stability than hydrous ethanol (95.0% purity), and the blended fuels could be produced at room temperature. Besides, adding ethanol resulted in a decrease in density and viscosity, as well as a change in cetane number, which led to improved engine characteristics [10, 23]. The stability time was mainly for the diesel mixed with 5% ethanol and <20% FAMEs, whereas the blended stability was more than two months [2, 26]. The diesel engine results using diesel mixed with <20% FAMEs and ethanol lowered the BTE compared to diesel. In comparison, the BSFC increased when fueling the mixture of FAMEs and <20% ethanol. The NO, CO, and BS were continuously reduced with increasing ethanol [2, 10, 23, 26]. Additionally, there were examinations of the operating behavior of the diesel engine at speeds and fixed loads running with the diesel and cottonseed methyl ester (CME) mixture in the proportion of 80:20 (namely CME20) combined with 10% ethanol. It released NO and CO levels lower than those of CME20 and diesel [27]. The use of CME20 mixed with 10% alcohols, such as butanol, ethanol, and methanol, was founded on the fact that the density and viscosity of CME20 blended with 10% alcohols were slightly higher than diesel but lower than CME20. The BTE of CME20 blended with 10% alcohol was similar to diesel, and it was higher than CME20. The NO was higher, but the CO was lower than diesel and CME20. The CME20 mixed with 10% ethanol had lower CO emissions than the blend of butanol and 10% methanol [28]. Similarly, there were experimental verifications of a common-rail diesel engine at 2,000 rpm and various torques when operated with COME20 mixed with 10% ethanol. It improved the BTE and BSFC better than COME20 and diesel, but the NO emissions increased. The carbon particulates dropped more than COME20 and diesel [29]. Moreover, the engine behavior at 1,500 rpm under different loads from using diesel blended with 20% rice bran methyl ester (RBME20) and combined with n-butanol added at 10% and 20% identified the changes in engine efficiencies. Nevertheless, the UHC, CO, and BS were higher than those of RBME20 and diesel [30].

Nowadays, the FAMEs are being globally used, especially the POME. In Southeast Asia, particularly in Thailand, POME can be produced from palm oil due to the cultivation of a large number of palm trees. [5-6, 12]. The diesel blended with 10% POME (POME10) is used in this country to replace conventional diesel, namely regular diesel (B10) [2]. POME20 is mainly used as renewable energy for heavy diesel engines, as allowed by the Energy Ministry in Thailand [26]. However, POME20 cannot be properly applied for light diesel engines due to the higher FD and KV than POME10 [5-6]. The earlier analysis on blending palm oil ester (POE) with ethanol used POME10 mixed with increasing ethanol up to 10%, close to the standard limit of diesel properties and similar engine performance to regular diesel at the same speed and load. The NO was escalated, and the CO has dwindled with increasing ethanol [31-32]. Contrarily, diesel mixed with 10% POEE (namely POEE10) combined with less than 20% ethanol improved the operating parameters of the diesel engine. Outstandingly, POEE10 blended with 5% ethanol had a BTE close to that of diesel, and its properties were better than POEE10. However, the decrease in BTE was proportional to the increase in ethanol. POEE10 combined with ethanol additives indicated the continuous decline of various pollutants, such as CO_2, NO, CO, and BS [2]. Similarly, POME10 properties were alleviated by blending 5% POEE and 5% butanol, combined with ethanol by up to 10%, which led to better fuel properties (FD and KV) and BTE than POME10. Their emissions were also decreased due to the addition of ethyl and methyl alcohol in the range of 5 to 10%, improving fuel properties and resulting in more complete combustion [26]. The separation of POME10 mixed with 10% ethyl alcohol was not observed after two months, and the FD and KV were the same for fossil diesel. The BTE was lower than POME10 and diesel, but the exhaust emissions were reduced as well [33-34].

From the literature [5-18] cited, the viscosity of diesel blended with 20% FAEs is higher than the diesel baseline, leading to changes in engine characteristics. Engine performance is especially reduced by using this blended fuel due to its fuel viscosity effects on injection timing, injection period, and combustion processes. As a result, exhaust emissions change, particularly the escalation of NO and the fluctuation of CO and CO_2 [5-7, 11]. Some researchers [2, 19, 26, 34] used conventional diesel mixed with a combination of methyl and ethyl ester up to 10% compared with common diesel, testing it in a single-cylinder engine at 3,000 rpm and different powers. Although the BSFC was faintly higher due to the lightly lower CV of this blended fuel, the BTE was better than diesel mixed with one of the esters because of the better combustion supported by more O_2 atoms. NO and CO_2 were less than diesel mixed with one of the esters. However, their engine performances were lower than the diesel baseline. The diesel blended with 20% FAEs can run with the low- and medium-speed diesel engines without any problems, but the adjustment of the fuel injection pump and the preheating fuel are suggested to apply to high-speed and common-rail direct injection diesel engines [35]. Therefore, one of the simplest methods is the addition of alcohols due to their low cost and the improvements in fuel-blended properties depending on alcohol types [10, 19, 22]. Ethanol has advantages in terms of low cost and less toxicity since it is produced by fermentation. Nevertheless, the use of diesel mixed with 10% ethanol gives rise to the dwindling of BTE due to the incomplete combustion, then the CO and UHC are enlarged and the rapid separation of fuel blended layers [2, 21, 23]. Conversely, the diesel-ethanol-FAE combinations can improve rapid separation, fuel viscosity, and engine characteristics, but they are dependent on the proportions of diesel, ethanol, and FAEs [10-11, 22, 31-32]. As a result, there is complexity in sampling to find the appropriate proportions. The diesel blended with 20% FAEs and 10% ethanol identified the BTE, and the combustion processes changed. Importantly, CO and UHC are added when compared with diesel blended with 20% FAEs [27-29]. Ethyl acetate (also known as ethyl ethanoate) is primarily used as a solvent and diluent. It is lower in price and toxicity than butanol and methanol, as its manufacturing process is the esterification of ethanol [3, 19, 21, 33-34]. The use of diesel blended with FAEs up to 10% combined with the sum of ethyl acetate and ethanol at 10% can improve fuel viscosity and reduce CO and UHC emissions. Eminently, it is similar in engine performance to the diesel baseline, and there is no separation of the fuel mixture over two months [34]. POME10 is becoming the main fuel in Thailand because of the sufficient amount of palm oil used in this country, and the Ministry of Energy in Thailand requires the use of POME20 for light and heavy diesel engines to reduce PM emissions. Notwithstanding, POME20 releases CO_2 and NO higher than POEE20 [5-6]. The experimental studies of POME10 mixed with 10% POEE becoming diesel combined with 20% POE (POE20) have not yet been examined. Additionally, POE20 blended with 5% ethyl acetate combined with up to 20% ethanol to fuel a high-speed diesel engine was rarely seen.

The main objective of the present work is the inquisition of the extensive properties of POE20 combined with ethyl alcohols, a constant ethyl acetate at 5%, and an anhydrous ethanol enlarged from 5 to 20%. Next, the combinations of POE20 and ethyl alcohols are tested with a vertical diesel engine at a high revolution of 3,000 rpm under various brake mean effective pressures to study the changes in the performance parameters and pollution products. All of the above investigations are compared with POE20 and conventional diesel to explain the results and novelties discovered.

2.0 METHODOLOGY

2.1 Preparation of Fuel Blends

The various substances and fuels in this research were ordinarily purchased from local gas stations, chemical companies, and marts in Thailand. First, the obtainable diesel was a regular diesel, namely B10 or POME10. It was tested using ASTM methods, such as density, viscosity, flash point, and LHV. They were compared with diesel specifications according to the announcement of the Energy Ministry in Thailand, and the various inspections are shown in Table 2. Next, ethyl alcohols used ethanol (without water) and ethyl acetate (a co-solvent). The anhydrous ethanol had 99.9% purity, and the ethyl acetate had 99.6% purity. They were also inspected according to ASTM standards. Eminently, POEE was synthesized from refined palm olein transesterified with anhydrous ethanol under sodium hydroxide (NaOH), as studied by Chinwanitcharoen et al. [5] and Sutheerasak and Chinwanitcharoen [23]. The yield of POEE was between 98.80 and 99.13%, as measured by a gas chromatography tester and in the official specifications of Thailand [2-3, 5].

Table 2. Fuel properties

Items	POE20:Ea:E	Price per liter	Density	Viscosity	Flash point	LHV	ST
	(% v/v)	(USD)	(kg/m^3)	(mm^2/s)	(°C)	(MJ/kg)	(days)
ASTM methods	-	-	D1298	D445	D93	D240	-
Diesel specifications	-	-	<870	<4.10	≥52	-	-
Regular Diesel	-	0.87	839	3.26	81	44.86	-
Ethanol	-	3.89	790	1.40	14	26.33	-
Ethyl Acetate	-	2.22	881	0.41	-5	22.80	-
POEE	-	1.17	872	4.75	174	39.87	-
POE20	100:0:0	0.90	846	3.82	85	43.67	N/A
POE20E5	95:0:5	1.05	841	3.61	27	42.06	N/A
POE20Ea5E5	90:5:5	1.12	844	3.47	18	40.83	N/A
POE20Ea5E10	85:5:10	1.27	837	3.30	14	39.01	43
POE20Ea5E15	80:5:15	1.41	828	3.21	11	37.98	12
POE20Ea5E20	75:5:20	1.56	819	3.10	9	35.13	1

Note: Currency exchange rate: USD 1 = THB 36.5

In cases of mixing various fuels, they were referred according to literature [2, 3, 19, 21, 23, 26, 34]. POEE at 10% v/v was mingled with regular diesel (POME10) at 90% v/v to make the POE20. Later, this oil was measured for various values under ASTM methods, and they were reported in Table 2. The results identified that the POE20 properties of FD, KV, and flash point were expanded by 0.83%, 20.25%, and 3.79 °C, and LHV was reduced by 1.53% compared with regular diesel, respectively. However, the POE20 properties were comparable to the specifications of diesel standards, indicating that they were within these scopes. To improve the POE20 properties, specifically FD, KV, and flash point, this work prepared POE20 by blending with ethyl alcohols (ethyl acetate and ethanol). The ethyl acetate was constant at 5% due to the higher density and lower LHV than ethanol (Table 2), and the ethanol was increased from 5 to 20%. The blending was accomplished according to the phase diagram study of the diesel-FAMEs-alcohol ratio in the literature [22-23, 31]. To investigate the stability of POE20-ethyl acetate-ethanol blended fuel as studied by Sutheerasak et al. [2] and Sutheerasak et al. [26], a jacketed glass reactor vessel and an electromagnetic stirrer were used to control the stirring speed, moisture content, and temperature for blend stability. The portions of POE20 at 90, 85, 80, and 75% v/v were merged with constant ethyl acetate (Ea) at 5% mingled with ethanol (E) enlarged by 5, 10, 15, and 20% v/v to make POE20Ea5E5, POE20Ea5E10, POE20Ea5E15, and POE20Ea5E20, respectively [26]. Additionally, this work also provided POE20E5 (95% POE20 blended with 5% ethanol) to compare with the POE20-ethyl acetate-ethanol blends. All mixtures were followed through a series of steps studied in the literature [26]. After the POE20-ethyl acetate-ethanol blends and POE20E5 were completed, the physical characteristics of these blended fuels were considered under various ASTM processes. The stability of these blended fuels was inspected for stratification time [2] and presented in Table 2.

Moreover, there was a cost analysis of combinations of POE20, ethyl acetate, and ethanol compared with the price per liter of regular diesel and POE20. The cost of POE20-ethyl acetate-ethanol blended fuel increased according to increasing ethanol prices. However, the price of POE20E5 and POE20Ea5E5 only rose by 20.57% and 28.16%, respectively, when compared with regular diesel. The results of POE20-ethyl acetate-ethanol blended fuel properties are comparable in physical properties to those of POE20, except for LHV. POE20 mingled with constant ethyl acetate at 5% and ethanol expanded from 5-20% indicated the reduction of FD, KV, flash point, and LHV by 0.24 to 3.19%, 11.73 to 19.13%, 67.32 to 76.32 °C, and 6.50 to 19.56%, respectively, compared to POE20. POE20Ea5E5's FD and KV were higher than regular diesel but lower than POE20E5. However, the LHV was less than regular diesel and POE20E5 because of the inferior CV of alcohols. Importantly, the POE20Ea5E10 gave the FD and KV close to regular diesel, but the LHV was reduced by 12.04%. POE20Ea5E20's FD, KV, flash point, and LHV were dropped by 2.38%, 2.76%, 72.53 ºC, and 20.79%, respectively, compared to regular diesel. For the stratification time (ST), POE20, POE20E5, and POE20Ea5E5 did not stratify after two months, except for POE20. However, POE20Ea5E10, POE20Ea5E15, and POE20Ea5E20 were separated after 43 days, 12 days, and one day, respectively.

2.2 Instrumentation and Measurement

The various fuels are burned in a vertical diesel engine of the Mitsuki, MIT-186FG model under high revolution by connecting with an electric dynamometer (ED). The maximum electrical power is produced by 5 kW at 3,000 rpm from running diesel baseline, as studied from the TIS-787-2551m's standard [19]. Figure 1 shows the design and installation of various equipment in this research. This engine used in the test does not have any modified equipment, and the engine details are listed in Table 3.

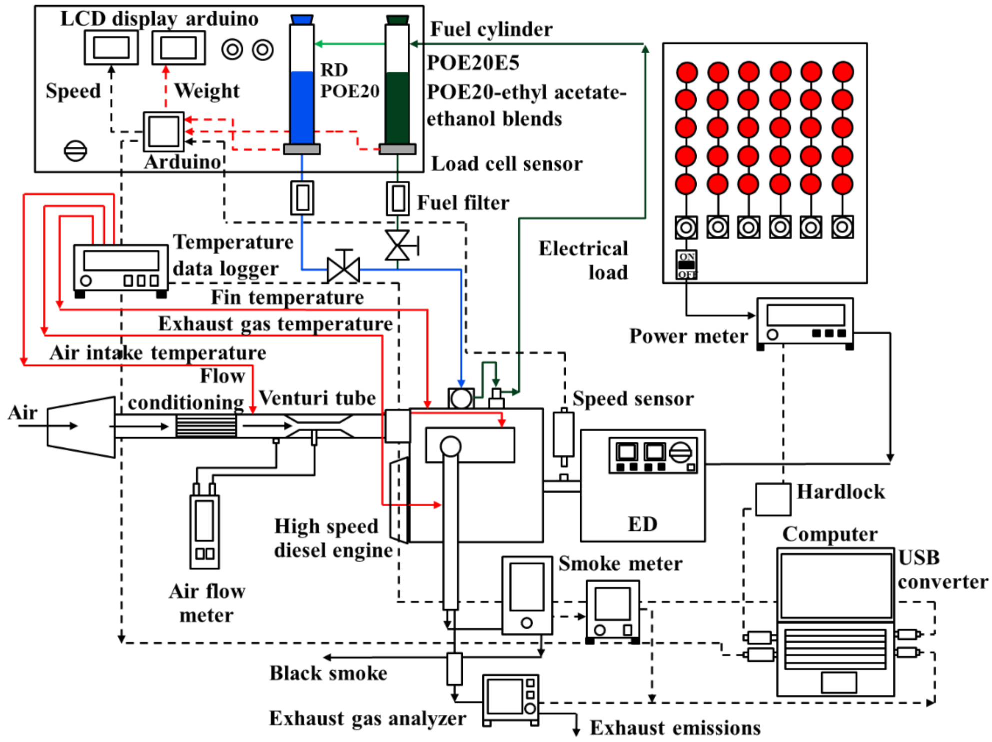

Figure 1. The experimental diagram of this research

To check the engine operation at various electric loads, the high-speed engine produced electric power from the ED by adjusting dimmers connected to the lightbulb array. A digital multi-function power meter connecting to the current transformer was applied to measure the electrical power, and it was recorded by a computer via a USB converter. For controlling the various engine temperatures, the K-type thermocouples were linked with a temperature data logger (Agilent, Model 34970A Data Acquisition) to capture various data on the intake, fin, and exhaust temperatures displayed on the computer. Flow condition control and air flow measurement used a flow conditioning tube, venturi pipe, and air flow instrument. To record the fuel consumption rate, this work also brought a fuel cylinder onto a load cell sensor with Arduino processing on an LCD display. The engine speed was recorded by using a speed sensor connected to the same Arduino system.

Table 3. Details of a high-revolution diesel engine

Items	Descriptions
Layouts of engine	Reciprocating, 4-stroke cycle, direct-injected chamber, and air-cooled
Designs of fuel system	4 holes and mechanical injector and pump
Cylinder (cyl)	1
Compression ratio	17.5:1
Bore x Stroke (mm)	86 x 70
Max power per cylinder (kW)	8.5
Engine speed (rpm)	3,000

Importantly, the studies of exhaust products used the measurements of a Cosber KWQ-5 Automotive emission analyzer for recording CO_2, UHC, CO, and NO. Likewise, PM calculations were derived from the BS measurements using a Cosber KYD-6 Opacimeter. Recording various values of the exhaust products was also displayed on the computer. The range and accuracy details are indicated in Table 4. After measuring the gas emissions by volume, their units were eventually converted to the mass basis of a g/kWh unit [27].

Table 4. Various measuring areas

Measurements	Units	Methods	Range	Accuracy
CO_2	%vol	Non-disperse Infrared	0-18	±0.02
UHC	ppm	Non-disperse Infrared	0-10,000	±1.00
CO	%vol	Non-disperse Infrared	0-15	±0.02
NO	ppm	Electrochemical Cell	0-5,000	±1.00
BS	%	Opacity	0-100	±0.20

2.3 Experimental Steps

The engine tests with POE20-ethyl acetate-ethanol blends, POE20E5, POE20, and regular diesel were studied for 100 hours of operation following the schemes described in the literature [2, 26]. The results of engine operation were repeatable five times. The steps of the experiment are the following:

i) The experiment started with warming up the engine by approximately fifteen minutes using regular diesel (RD) to stabilize at a set running hot fin temperature.
ii) The speed had been increased to 3,000±50 rpm. The air intake manifold and air surrounding temperatures were controlled at 30±5ºC after stabilization of the engine fin temperature. After the engine stabilization at 3,000±50 rpm without load, various parameters (electrical power, air flow rate, temperatures, and exhaust products) were also measured.
iii) After recording the no-load parameters, the electric load was increased by 20%. Fuel mass was controlled at 17g to measure the time of fuel consumption for calculating the fuel consumption rate. Simultaneously, various parameters were also examined.
iv) After finishing 20% of the electrical load records, the electrical load was raised to 40%, 60%, 80%, and 100%, respectively. In each workload, various values were recorded step-by-step.
v) After the engine running on RD was accomplished, the POE20 and POE20 mixed with alcohols were inspected in order: POE20, POE20E5, POE20Ea5E5, POE20Ea5E10, POE20Ea5E15, and POE20Ea5E20, respectively. The sequence of various fuel mixtures was tested under the same conditions as the RD tests, where all variables were recorded to compare with RD.
vi) The measured variables by fueling with RD, POE20, and POE20 mixed with alcohols were used to calculate the values of performance and emission characteristics.

2.4 Data Analysis

The performance and emission characteristics were studied from the brake thermal efficiency (BTE), the brake specific fuel consumption (BSFC), and the standards of European vehicle emissions [27, 34], as calculated as follows:

$$BTE = \frac{P_{ele}}{\dot{m}_f . Q_{HV,f}} \tag{1}$$

$$BSFC = \frac{\dot{m}_f}{P_{ele}} \tag{2}$$

$$CO_2\ (g/kW.h) = 63.47\ x\ CO_2\ (\%vol) \tag{3}$$

$$UHC\ (g/kW.h) = 2.002\ x\ 10^{-3} x\ UHC\ (ppm) \tag{4}$$

$$CO\ (g/kW.h) = 35.91\ x\ CO\ (\%vol) \tag{5}$$

$$NO\ (g/kW.h) = 6.636\ x\ 10^{-3} x\ NO\ (ppm) \tag{6}$$

$$PM\ (\mathrm{g/kW.h}) = \frac{C\ (\mathrm{mg/m^3})\ \mathrm{x}\ 3.6\ \mathrm{x}\ VFR}{P_{ele}} \tag{7}$$

where P_{ele} was the electrical power, $\dot{m}_f$ showed the fuel consumption of fuels, $Q_{HV,f}$ was the lower heating value of fuels. The universal conversion of CO_2, *UHC, CO,* and *NO* (% v/v or ppm) to BSFC (g/kW.h) for the European vehicle emissions standards was studied by Ağbulut et al. [28] and Sutheerasak et al. [34]. For the *PM* measurement, the volume flow rate (*VFR*) of exhaust gas and *C* (mg/m^3) were the correlation of filter smoke number depended on black smoke intensity, as referred by Sutheerasak et al. [34].

3.0 RESULTS AND DISCUSSION

The prepared fuels are studied in a diesel engine at a high speed of 3,000±50 rpm, and the engine loads added at 20, 40, 60, 80, and 100% are principally analyzed in terms of the brake mean effective pressure (BMEP). It was calculated by the ratio of the electrical power per speed of the cylinder's displaced volume per cycle. All experiments were controlled for the loads by the electrical powers at 0.93±0.02, 1.92±0.01, 2.83±0.02, 3.65±0.03, and 4.45±0.07 kW_{ele}, respectively. Then, they were transformed into BMEP values of 89.27±0.07, 185.19±1.05, 273.85±0.39, 353.58±0.27, and 432.20±1.61 kPa, respectively. Additionally, the air flow rate was 7.146±0.0005 kg/hr. The test fuels lead to the different parameters as reported below.

3.1 Brake Thermal Efficiency

Brake thermal efficiency (BTE) is the ratio of the electrical power and the multiplication of fuel consumption according to engine tests and LHV (Eq. (1)). As shown in Figure 2, the increase in BTE matches the increase in BMEP. The maximum value of BMEP was found at 354 kPa (80% load), as the input energy supplied to the engine was properly converted to electrical power. However, the engine running at full load caused the alleviation of BTE because of the greater accumulation of mechanical losses [2-3, 5-6].

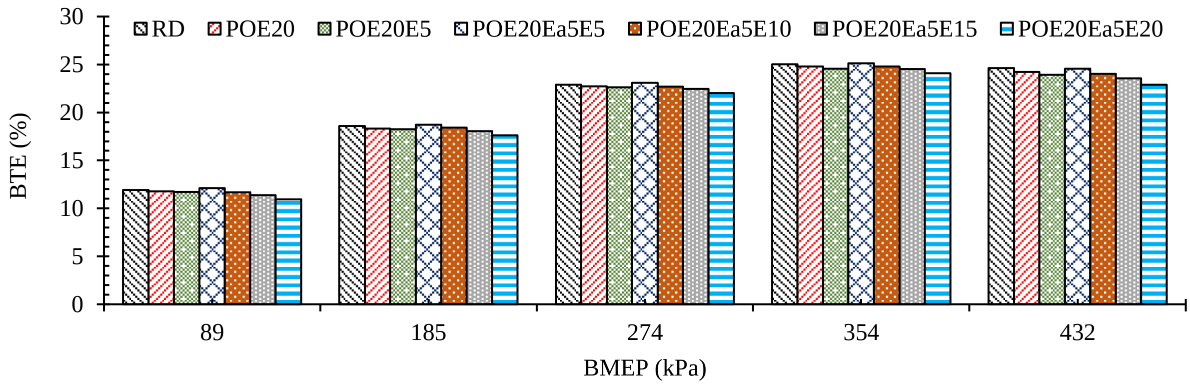

Figure 2. BTE at a different BMEP

The results were mainly explained at 354 kPa (80% load) to reflect a real engine capability. The BTE values for blended fuel combustion have changed in several aspects, as follows: (i) POE20 and POE20E5 lowered the BTE of RD by 0.86% and 1.79%, respectively, due to their lower LHVs (see Table 2), giving rise to the increased fuel consumption rate when generating the same power output [26]. (ii) POE20Ea5E5 showed a subtle higher BTE than RD, POE20, and POE20E5 by 0.47%, 1.34%, and 2.30%, respectively. It was assumed that the increased oxygen content from blending ethyl acetate and ethanol led to more complete burn zones, and then the BTE improved [26]. (iii) The engine was fueled with POE20Ea5E10, POE20Ea5E15, and PEE5Ea5E20 results, contrary to POE20Ea5E5 in terms of BTE, which dropped by 0.89 to 3.70% and 0.03 to 2.87% compared with RD and POE20, respectively. It was clarified that the increasing ethyl alcohols by upwards of 10% identified the serialized letdown of energy value, giving rise to an accretion of fuel injection to maintain the same electrification [3]. (iv) The main findings show that the use of POE20Ea5E10 improved the BTE more than POE20E5 by 0.92% since the ethyl acetate resulted in a complete combustion increase in burning phases better than the only ethanol [10, 22]. The use of POE20Ea5E15 and POE20Ea5E20 lowered BTE compared to POE20E5 by 0.22% and 1.95%, respectively. These results were consistent with those found by Santasnachok et al. [3] because the increment of ethanol higher than 10% affected the continuous dwindling of BTE due to the serialized reduction of LHV and the increased fuel consumption.

3.2 Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) is a division between fuel consumption and electrical power (Eq. (2)), as reported in Figure 3. BSFC was correspondingly reduced with increasing BMEP. These results were agreed upon by earlier studies [2-3, 5-6] because the brake power increased more than the fuel consumption, leading to a continuous reduction of BSFC at the same engine revolution and cylinder displacement volume. In addition, the fuel injection period and the fuel conversion efficiency were appropriate to the engine power produced [21, 23]. The lowest BSFC occurred at 354 kPa of BMEP. The subsequent results were consistent with the trend of BTE from previous studies [2-3, 16], where the trend of BSFC was in opposition to BTE. The blended fuel POE20 consumed more fuel in terms of BSFC by 2.44% compared to RD. This was consistent with Sutheerasak and Chinwanitcharoen [23], as the increment in POE fraction led to a reduction in CV, and then fuel consumption was raised when tested at an equal electrical power level.

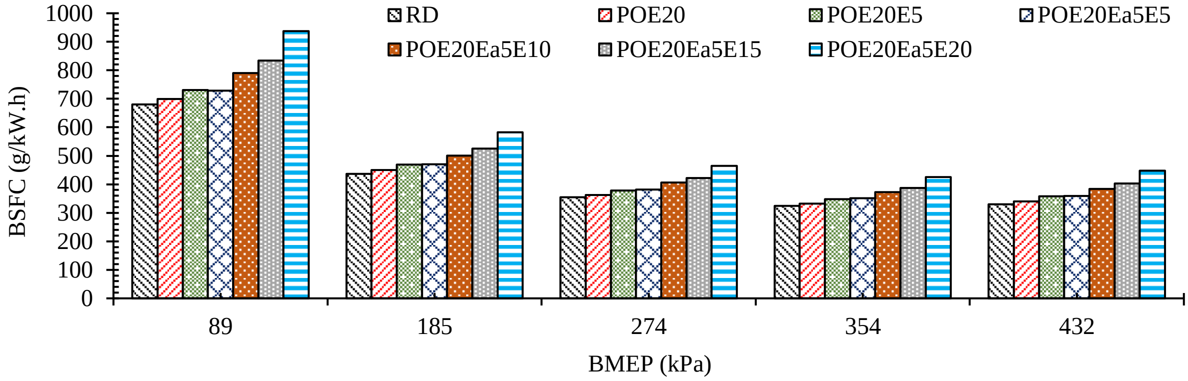

Figure 3. BSFC at a different BMEP

The use of POE20E5 and POE20Ea5E5 had a similar BSFC. Nevertheless, POE20E5 was slightly lower in BSFC than POE20Ea5E5, since the density of POE20E5 was trivially lower and the LHV was slightly higher than POE20Ea5E5 (see Table 2). When they equally generated power, the fuel consumption of POE20Ea5E5 was trivially higher. They were enlarged by 7.36% and 8.12% in BSFC, respectively, compared with RD. Additionally, the POE20 merged with constant ethyl acetate combined with increasing ethanol from 10 to 20% resulted in a huge increase in the BSFC. They increased from 14.71 to 31.10%, 11.98 to 27.98%, and 6.84 to 22.11% compared with RD, POE20, and POE20E5, respectively. These results were in line with those reported by Santasnachok et al. [3], explained by the fact that a combination of ethyl acetate and ethanol higher than 10% led to further abatement of LHV. Although these blends improved fuel density and viscosity, the energy value of these blends was much less than that of RD, POE20, and POE20E5 (see Table 2 for a comparison of values). Therefore, the total energy supplied by these blends was greater than that of RD, POE20, and POE20E5, affecting the accretion of BSFC.

3.3 Carbon Dioxide

Exhaust gas products from complete combustion consist of carbon dioxide (CO_2), water vapor ($H_2O(g)$), and nitrogen (N_2). CO_2 has primarily been produced from the carbon (C) molecules of fuels and oxygen content in the surrounding air (O_2) within the combustion chamber in complete combustion conditions [21, 26, 34]. The variation in CO_2 release from the test fuels was investigated by Eq. (3), and it is shown in Figure 4. CO_2 level increased with increasing BMEP because the consumption of fuel was appropriately increased with enlarging power, and the use of high-revolution engines had escalated air flow and O_2 content in the combustion chamber. Therefore, the more complete combustion was enhanced with increasing BMEP, leading to the continuous addition of CO_2. These results were confirmed by the literature [8, 12, 34-35]. The blended fuels combusted in this engine resulted in a change in CO_2 release. POE20 increased CO_2 emissions by 2.17% compared to RD. This result was encouraged by those in Chinwanitcharoen et al. [5] and Santasnachok et al. [6], as the increasing POE portion in the mixture led to the accretion of O_2 content, causing complete combustion in the premixed region, leading to CO_2 production. Contrarily, POE20 mixed with 5% ethanol resulted in reducing CO_2 levels by 1.63% compared with POE20. This result was established by Sutheerasak et al. [2] and Niculescu et al. [10], as postulated by decreasing molecules of C within blending POE20 with ethanol and increasing molecules of hydrogen and oxygen, causing the hydroxyl radical (OH) formation. Figure 4 also shows the continuous escalation of CO_2 release in POE20-ethyl acetate blended fuel with an increasing ethanol fraction from 5 to 20%. CO_2 increased by 2.58 to 6.89%, 0.41 to 4.62%, and 2.07 to 6.35%, compared with RD, POE20, and POE20E5, respectively. Increased by 0.41% was the CO_2 release of POE20Ea5E5 over POE20. These results were agreed upon by the literature [3], as clarified by the constant ethyl acetate and additive ethanol up to 20% mixing with POE20, which continuously increased oxygen molecules and caused a greater extent of complete combustion. As a result, CO_2 release was increased.

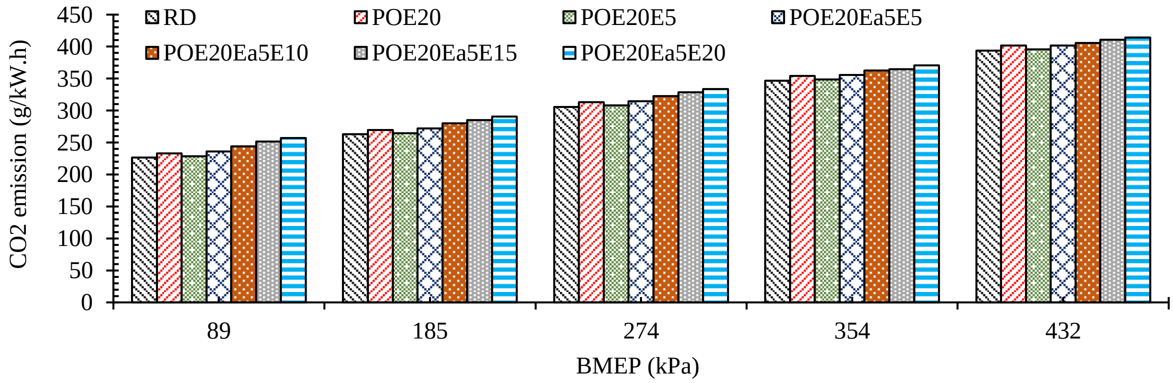

Figure 4. CO_2 at a different BMEP

3.4 Unburned Hydrocarbons

The unburned hydrocarbons (UHC) on a mass basis were calculated from Eq. (4) and depicted in Figure 5. Basically, the UHC occurs from inferior combustion quality at fuel-rich combustion in cases of low and high power from changing fuel consumption [8, 12]. In this test, the UHC decreased with increasing MEP since fuel consumption had been increased to match the engine power produced, and there was more O_2 from using high engine speed. As a result, the more complete combustion increased with increasing BMEP, leading to the continuous reduction of UHC [34]. Moreover, these results were agreed upon by earlier studies [2, 9, 26, 34], and they were consistent with an increase in CO_2 in the previous section. POE20 reduced UHC emissions by 6.98% compared to RD. This result was consistent with Sutheerasak et al. [34] due to the high O_2 concentration from using POE20, resulting in more complete combustion than RD. On the other hand, the use of POE20E5 and POE20-ethyl acetate-ethanol blends was different. In cases of POE20E5, the UHC emission was reduced by 6.98% compared with RD due to the high O_2 content from blending POE with ethanol, leading to more complete combustion than RD [2, 26, 34]. However, the UHC level increased by 5.26% compared with POE20. It was assumed that the quick vaporization of ethyl alcohols gave rise to the accumulation of unburned fuel within areas of the combustion chamber, causing an increase in UHC emissions [2, 26, 34]. In terms of POE20-ethyl acetate-ethanol blends, the UHC emission has continuously increased with increasing ethyl alcohols. Figure 5 also indicates the continuous addition of UHC to the release of POE20-ethyl acetate blended fuel with an increasing ethanol fraction from 5 to 20%. UHC was raised by 6.40 to 58.14%, 20.39 to 78.95%, and 14.38 to 48.63%, compared with RD, POE20, and POE20E5, respectively. Increased by 20.39% was the UHC release of POE20Ea5E5 over POE20. These results were in line with the literature [34] since the ethyl alcohols added by more than 5% led to a faster evaporation rate than RD, POE20, and POE20E5. As a result, fuel-oxygen combustion was inferior, and unburned fuel impingement on the chamber walls was highly increased, causing an increase in UHC emissions.

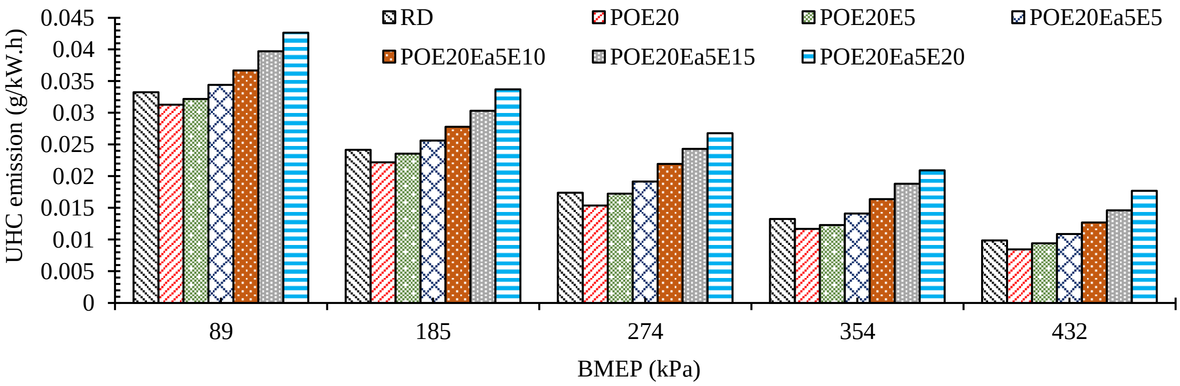

Figure 5. UHC at a different BMEP

3.5 Carbon Monoxide

The carbon monoxide (CO) from burning blended fuel is compared to those of RD, POE20, and POE20E5 converted to mass basis using Eq. (5), as shown in Figure 6. CO emissions are shown to reduce with increasing BMEP, and these results are consistent with the literature [2-3, 5-6]. Fundamentally, the increase in CO occurred from the incomplete combustion of the local fuel-rich mixture region. The use of high engine speed led to a higher O_2 concentration, and then there was an improvement in combustion and a reduction in CO emissions [12-13]. A mix of different fuels affects CO formation. The CO from burning POE20 and POE20E5 was lower than RD by 5.88 and 9.69%, respectively. These results were in agreement with those reported in previous studies [2, 12, 26, 33-34] due to the fact that combustion was better with higher O_2 concentrations. Furthermore, the decline in CO also coincided with the increase in CO_2, as shown in the previous section. The POE20-ethyl acetate-ethanol blends had dropped the CO according to increased alcohols. CO from using POE20 mixed with 5% ethyl acetate and ethanol increased from 5 to 20% was relieved from 12.46 to 22.49%, 6.99 to 17.65%, and 3.07 to 14.18% compared with RD, POE20, and POE20E5, respectively. These results were supported by the results of the literature [3, 8, 34] because the escalation of alcohols led to the continuous addition of O_2 elements, supporting complete combustion highly. As a result, the CO emission was less than RD, POE20, and POE20E5.

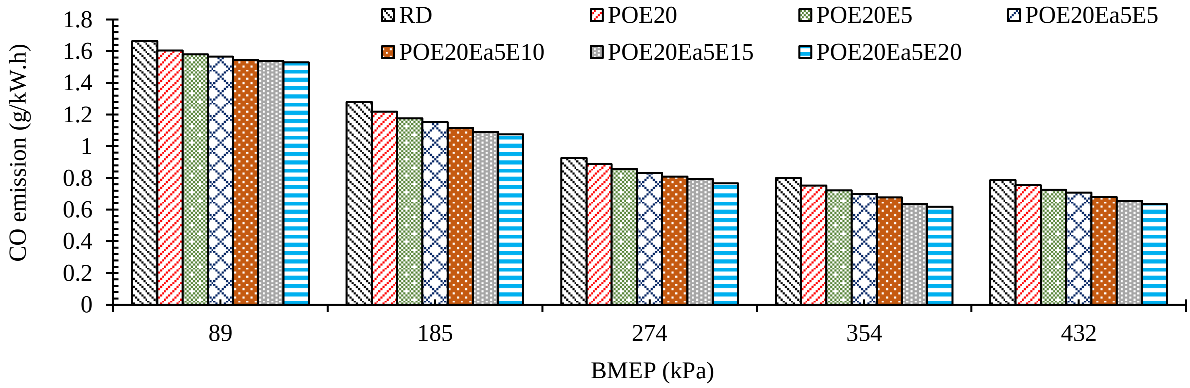

Figure 6. CO at a different BMEP

3.6 Nitric Oxide

Nitric oxide (NO) is a common designation for nitrogen oxides formed at high flame temperatures with abundant oxygen concentrations [2, 8, 12, 26, 34-35]. NO release from fuel blends is shown in Figure 7 (calculated by Eq. (6) on a mass basis); the NO emission increased with increasing BMEP. These results were confirmed by the literature [8, 12, 34] due to the higher O_2 content from using high engine speed, leading to high cylinder combustion. As a result, the flame temperature increased, leading to the NO escalation. The blended fuels were influential on engine combustion, resulting in a change in NO release. POE20 and POE20E5 generated NO emissions to a greater extent than RD, even though the ethanol was 5% mixed with POE20. They were increased by 3.31 and 0.87%, respectively.

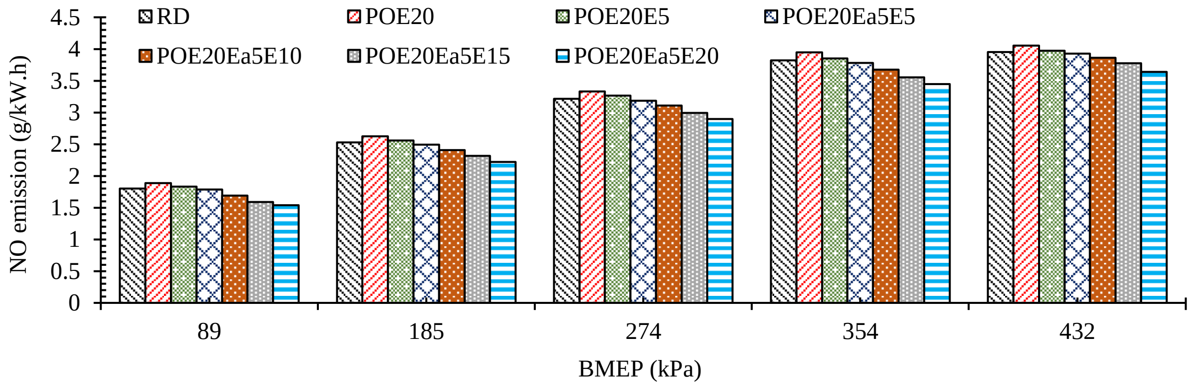

Figure 7. NO at a different BMEP

POE20 and POE20E5 contained a greater content of O_2 that promoted chemical reactions within the rapid combustion zone, and then the burning temperature was raised by providing more time for NO formation in an oxygenated environment [5-6, 12, 26]. POE20E5 released a lesser amount of NO than POE20, where the latter had fewer oxygen molecules to form NO under high flame temperatures. Furthermore, the POE20 mixed with ethanol increased the flame temperature in the burning zones so that the combustion gas could expand faster, thereby lowering the flame temperature. Additionally, the POE20-ethyl acetate-ethanol blended fuels resulted in a continuous reduction of NO emissions. The investigation of fueling POE20 mixed with 5% ethyl acetate and ethanol, increasing from 5 to 20%, has been found to reduce the NO release by 1.02 to 9.76%, 4.19 to 12.65%, and 1.87 to 10.53%, respectively, compared with RD, POE20, and POE20E5. These results were in line with Sutheerasak et al. [26] and Sutheerasak et al. [34] due to the continuous letdown of carbon atoms and the supplementation of hydrogen-oxygen concentrations of esters. In this circumstance, the cumulative escalation of OH formation was raised, increasing water vapor. Meanwhile, the rapid vaporization rate of ethanol can be a cause of a dropped auto-ignition temperature. Thus, the burning temperature within the rapid combustion region was dropped, affecting the abatement of NO during alcohol augmentation.

3.7 Particulate Matter

The black smoke (BS) basically occurs in the non-premixed zone to form particulate matter (PM). Figure 8 indicates the release of PM calculated from the multiplication of the volume flow rate of exhaust gas and the correlation value depending on the percentage of BS per the electrical power (Eq. (7)). The PM emission increased with increasing BMEP, but the PM release decreased with the use of blended fuels.

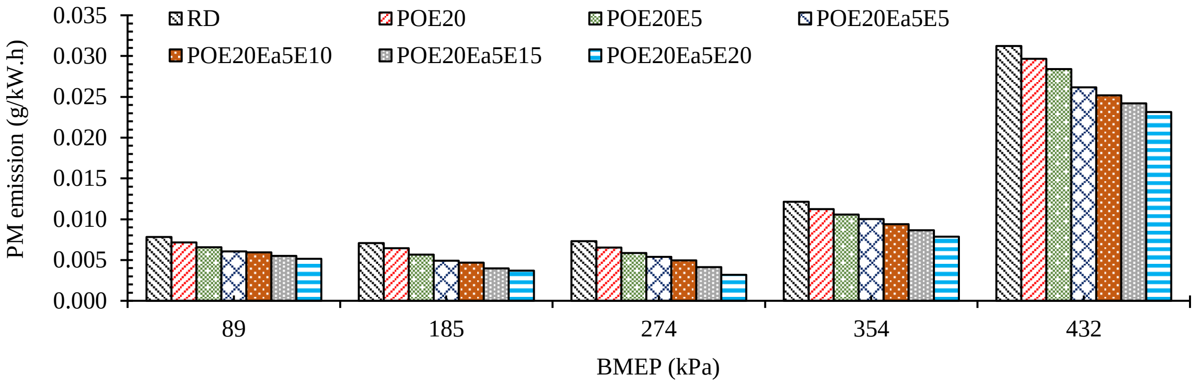

Figure 8. PM at a different BMEP

In cases of PM escalation with BMEP addition, these results were supported by earlier studies [8, 12, 21, 23], as the increase in fuel consumption corresponded to the increase in electrical power. As a result, the main fuel injection in mixing-controlled combustion was longer, resulting in more PM formation. Nevertheless, the use of blended fuels added oxygenated molecules, leading to an improvement in the mixing-controlled combustion phase. As a result, there was better combustion in this burning zone, leading to a reduction in PM emissions. These results were supported by the literature [5-7, 10-11, 34]. In cases of POE20 and POE20E5 compared with RD, the PM emissions were reduced by 7.59% and 12.90%, respectively. These results were agreed upon by the BS results, as identified in Figure 9. The increase in BS corresponded to the increase in BMEP, but the use of blended fuels caused the lessening of BS. POE20 and POE20E5 had lower BS emissions than RD by 6.64% and 11.52%, respectively. They were in line with the literature [2, 12, 26, 33, 34] due to the existence of O_2 content in both fuels, resulting in awfully complete combustion in the non-premixed zone, leading to the decreasing BS opacity. As a result, PM emissions decreased according to the reduction of black smoke emissions.

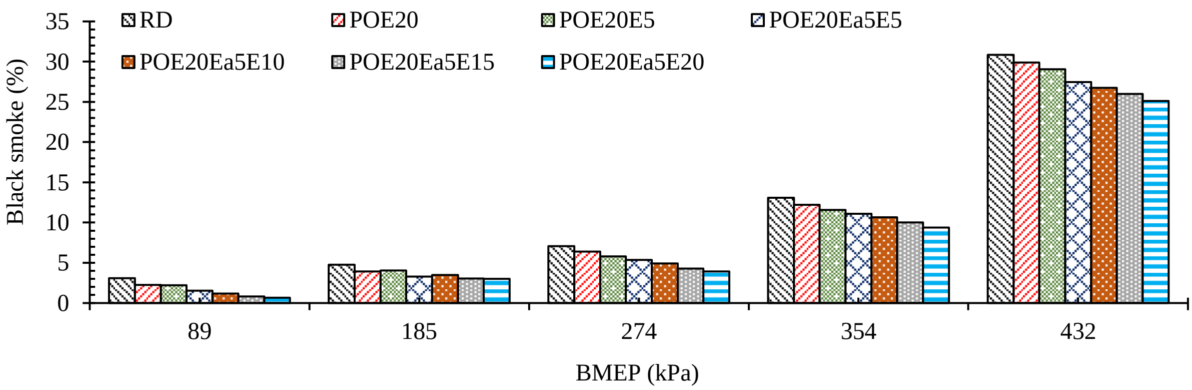

Figure 9. Black smoke at a different BMEP

Outstandingly, the use of POE20 mixed with constant ethyl acetate combined with ethanol increased from 5 to 20%, leading to the continuous reduction of PM emissions by 17.53 to 35.18%, 10.76 to 29.86%, and 5.31 to 25.58%. The black smoke emissions decreased from 15.16 to 28.38%, 9.13 to 23.29%, and 4.12 to 19.06%, compared with RD, POE20, and POE20E5, respectively. In addition, these results were in line with those published in the previous studies [2, 3, 26, 33-34] because the additive alcohols blended with POE20 resulted in a lesser C molecule reduction and plenty of O_2 molecule accretion. It was assumed that the more complete combustion within the diffusion phase led to a change in product species, especially the increase in CO_2 and the decrease in CO, which affected the change in black smoke and PM emissions. As a result, PM and black smoke releases decreased with increasing alcohol.

4.0 CONCLUSIONS

i) The experimental studies of the physical properties, performance parameters, and exhaust products of a diesel engine at high speed fueled by POE20 blended with ethyl alcohols can be concluded as follows:

ii) The POE20's density and viscosity are higher than RD. Additive alcohols can improve both properties. Subsequently, POE20Ea5E10 is similar to RD in fuel density and viscosity, but its LHV was reduced by 12%. Increasing ethanol up to 20% led to a continuous reduction of fuel density, viscosity, and LHV, and the stratification time occurred within a day.

iii) In terms of performance, POE20 and POE20E5 lowered the BTE more than RD as a result of increasing BSFC. The BTE can be improved by using POE20Ea5E5. The BTE increased by 0.47%, 1.34%, and 2.30%, respectively, compared with RD, POE20, and POE20E5. However, the POE20 blended with 5% ethyl acetate combined with an ethanol additive reduced BTE from 10 to 20%, resulting in a continuous reduction of BTE. The escalation of ethanol lowered fuel density and LHV, which increased fuel consumption at the same electrical power output.

iv) In terms of exhaust products, CO_2 emissions from POE20 were higher than those from RD. POE20 and 5% ethanol can mitigate the released CO_2. The continuous accretion of the ethyl alcohol mixture in POE20 escalated CO_2 emissions. POE20 blended with 5% ethyl acetate combined with ethanol up to 20% increased CO_2 emissions by 6.89%, 4.62%, and 6.35%, respectively, compared to RD, POE20, and POE20E5. The main advantages of these blended fuels are associated with NO, CO, and PM releases. These emissions were continuously reduced with increasing alcohols due to the higher O_2 concentration, resulting in highly complete combustion.

The experimental studies of POE20 blended with ethyl alcohols in a high-speed diesel engine have identified a preliminary conclusion of performance and emission characteristics, but the effects of fuel injection, spray, and combustion characteristics from using POE20 blended with ethyl alcohols have not yet been revealed, which are limitations of the study. Because the changes in performance and emission characteristics are explained by the changing physical and chemical properties of fuel blends, they predict a wide range of effects from engine operation. Therefore, this research work proposes that studies of fuel injection, spray, and combustion characteristics by using POE20 blended with ethyl alcohols, a re-calibration for fuel injection strategies, and using aftertreatment systems should be considered for future work. Furthermore, a long-term wear performance test of the diesel engine using POE20, POE20E5, and POE20Ea5E5 in comparison is suggested for setup.

5.0 ACKNOWLEDGEMENT

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7.0 NOMENCLATURE

BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
BS	black smoke
CO	carbon monoxide
CO_2	carbon dioxide
CV	calorific value
FAEs	fatty acid esters

FAEEs	fatty acid ethyl esters
FAMEs	fatty acid methyl esters
FD	fuel density
KV	kinematic viscosity
LHV	lower heating value
NaOH	sodium hydroxide
NO	nitric oxide
PM	particulate matter
POE	palm oil ester
POE20	diesel blended with 20% POE
POE20E5	POE20 mixed with 5% ethanol
POE20Ea5E5	POE20 mixed with 5% ethyl acetate and 5% ethanol
POE20Ea5E10	POE20 mixed with 5% ethyl acetate and 10% ethanol
POE20Ea5E15	POE20 mixed with 5% ethyl acetate and 15% ethanol
POE20Ea5E20	POE20 mixed with 5% ethyl acetate and 20% ethanol
POEE	palm oil ethyl ester
POEE10	diesel blended with 10% POEE
POME	palm oil methyl ester
POME10	diesel blended with 10% POME
POME20	diesel blended with 20% POME
RD	regular diesel
UHC	unburned hydrocarbons