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Comparison between PEE10 and PEE10-Bioethanol Blends on Performance and Emission Characteristics of a HSDI Diesel Engine

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Abstract

Biofuels are an alternative fuel currently being developed to reduce the diesel-engine environmental impact. The release of carbon dioxide (CO_2), nitric oxide (NO) and black smoke (BS) becomes an issue derived from diesel engines even in lean-mixture combustion causing an adverse effect to human health. The main aim of the research study is to present the use of biofuels, a mixture of diesel and 10 % palm oil ethyl ester (PEE10) and PEE10 blended with bioethanol from 5 to 20 %, compared with conventional diesel fuel. The biofuels were run on a high-speed direct injection diesel engine at a constant speed of 3,000 rpm under various loads. The use of PEE10 resulted in brake thermal efficiency (BTE) reduction by 2 % and brake specific fuel consumption (BSFC) incrementation by 8 %, but the exhaust emissions were lower than diesel, except for CO_2 and NO. However, PEE10 engine performance was better and exhaust gas emissions were lower for both pollutants than diesel mixed with 10 % bioethanol. The investigation of PEE10 with increasing bioethanol revealed that the use of PEE10 blended with 5 % bioethanol (PEE10E5) can improve engine performance, while the BTE and BSFC were close to that of diesel, and exhaust emissions, especially CO_2, NO and BS reduced. Moreover, BTE from PEE10E5 fueling increased by 2 % but BSFC was subtle increased, compared to PEE10. On the other hand, the increasing bioethanol from 10 to 20 % in PEE10 led to the more reduction in engine performance, but the engine pollutants were also continuously decreased. Specifically, the blend of PEE10 and 20 % bioethanol indicates that CO_2, NO and BS were reduced by 10, 15 and 33 %, respectively, compared to diesel fuel.

Keywords: Bioethanol, Diesel engine, PEE10, Performance, Pollutants

Introduction

Diesel engine is widely applied to agricultural mechanics, electrical generators, small power plants and vehicles. Pollutants released from diesel engines, particularly CO_2, NO and particulate matter (PM) in term of BS, are now become an issue as an impact on public health that is steadily worsening and hardly controlled in Thailand. Therefore, the addition of oxygenated additives, alcohols and esters, to conventional diesel fuel has been continuously studied. Various methods were tested and applied to strengthen fuel additives comprising emulsification, esterification, fumigation and modification.

Fumigation and modification are more complex and expensive, and emulsification is recently studied based on unmodified engine at low cost but effective reduction in exhaust emissions [1]. Diesel-alcohol blended fuels by using emulsion processes affected on performance, combustion and emission characteristics of diesel engines at speeds and loads were proven in a number of research studies. Alcohols, especially ethanol, ethyl acetate, methanol and butanol, are competitive renewable fuels due to high oxygen (O) content that promotes more complete combustion in combustion zones of diesel engines [2]. The combining diesel with increasing alcohols led to the reduction of BTE and the increase in BSFC due to the lower energy value of alcohol [1,2]. Bioethanol which was an ethanol made by microbial fermentation could be produced from agricultural crops, and it was less toxic and cheaper than other alcohols. The mixtures of conventional diesel and bioethanol is one of the promising alternative fuels.

The diesel-bioethanol blended fuels resulted in the reduction of exhaust gas compositions, such as CO_2, NO and BS. Total unburned hydrocarbons (THC) and carbon monoxide (CO) were changed, depended on the proportion and purity of bioethanol. However, the blended fuel stability reduced with increasing bioethanol proportion [2,3].

Another method directly used in diesel engines without modifications at high stability of fuel mixture combustion is fueling esterified products such as plant oils (edible, non-edible and waste oils) reacted with alcohols (methanol and ethanol) and catalysts to form methyl ester (ME) and ethyl ester (EE) [4]. Several studies in [4,5] investigated the characteristics of low-speed direct injection (LSDI) diesel engines at speeds and loads. ME were produced from renewable oils, such as coconut, calophyllum inophyllum, castor, jatropha, juliflora seeds, palm, soybean and waste cooking, reacted with methanol and catalysts to synthesize CME, CIME, CSME, JME, JSME, PME, SME and WCME, respectively. The use of these esters compared with diesel revealed that the reduction of BTE was by 4 % or more, and the increase of BSFC was more than 20 %. This was due to the higher fuel density and viscosity and lower calorific value (CV) of the esters compared to that of diesel. CO and THC were enlarged more than 10 % from using CME, JME and WCME, but CO, THC and BS were dropped from using PME and SME, except for CO_2 and NO that were highly increased [6,7]. Engine performance was little changed by using diesel blended with 10 % PME (PME10), but BSFC from combining diesel with SME, JME and WCME at 10 % was higher than PME10. CO_2 and NO from using these blends were augmented, although CO, THC and BS were relieved [8]. The engine performance results at 80 % load using PME, palm oil reacted with methyl alcohol and potassium hydroxide catalyst, identified that BTE was decreased by 13 % and BSFC was increased by 30 %, compared with diesel but the PME10 resulted in the reduction of BTE and the addition of BSFC by 10 and 15 %, respectively [9].

Palm oil is recently selected for the main resource in producing the ME in Thailand, because palm trees are a year-round economic crop and the amount of oil per production area is higher than other oil-bearing plants (coconut, soybean and sunflower). Furthermore, another ester gaining more attention in terms of cost benefit and resource availability is EE [10]. Some researchers [10,11] produced palm oil ethyl ester (PEE), transesterified from palm oil, anhydrous ethanol (99.9 % of purity) and catalysts, potassium methoxide and sodium hydroxide (NaOH), and mixed with regular diesel (from 10 to 50 %). The PEE-diesel blended fuels have been operated with high-speed direct injection (HSDI) engines in whole range length of engine loads and speeds. Additionally, the performance test of LSDI engine using PEE, reacted by bioethanol and NaOH catalyst was performed, compared with blends of diesel and PEE (from 10 to 90 %) [12]. The use of PEE and its blends with base fuel compared with diesel was disclosed that the engine performance when burning the mixture of diesel and 10 % PEE (PEE10) was similar to diesel, but the mixtures of diesel and PEE more than 10 % led to the decrease of BTE and the increase of BSFC. CO, THC and BS were reduced, but CO_2 and NO were enlarged with increasing PEE. The production of EE by using NaOH catalyst was frequently examined, because this catalyst was at low cost [11,12]. Earlier studies of EE and EE-diesel blends found that the combining diesel with 25 % cardanol ethyl ester, cardanol oil reacted with ethyl alcohol (99 % purity) and NaOH, exhibited the same engine performance as diesel, but THC and BS were increased [13]. The use of camelina ethyl ester (CAEE), synthesized by camelina oil, bioethanol and NaOH, and diesel mixed with 20 % CAEE resulted in lower engine power and higher BSFC than diesel [14]. Comparison between EE and ME, produced from pongamia, mahua and waste frying oils reacting with alcohols and catalysts at equal catalyst ratio, showed that EE consumed more fuel (in terms of BSFC) but lower exhaust emissions than ME, although both esters brough about lower engine performance than diesel. The blends of diesel and both esters can improve engine performance, nevertheless CO_2 and NO raised with increasing esters [15,16].

Several works [17,18] presented that the exhaust emissions, especially CO_2 and NO, were altered by the combustion of the blends of diesel, esters and alcohols by emulsification, as mainly tested with the LSDI engines at speeds and loads. However, the allaying of both pollutants depended on the kinds of alcohol and ester and the proportions of mixture. Some studies [18,19] examined the phase stability and solubility of diesel-ester-bioethanol blends by using emulsion processes, since esters acted as better additives for bioethanol blending with diesel baseline. Moreover, the dramatic improvement in the bioethanol solubility within the diesel-ester mixtures in all proportions was depended on the blend temperature and the bioethanol purity. The diesel-ester mixtures combined with bioethanol (99.5 % purity and above) were subject to be in the blending temperature range of 30 to 40 ºC, because they were stable at all ratios. Nevertheless, the diesel mixing with esters and bioethanol, more than 20 %, was not stable and separated within 24 h. As a result, engine performance was greatly reduced and an enormous amount of CO and THC was released [16-19]. The antecedent experimentation of the ratio of diesel:PME:bioethanol (D:PME:B) predicated that the mixture at the ratio of D:PME:B at 90:5:5 had a

heating value similar to diesel while the mixture at the 80:15:5 ratio gave the highest cetane index, while both fuel blends were without the problem of phase separation. Furthermore, CO and THC were decreased, but NO was increased as compared with diesel [20]. The ratio of D:PME:B at 78:17:5 was optimum because of the highest stability, but the engine performance was subtle lower and the levels of CO_2 and NO were a bit higher than diesel baseline [21]. The ratios of D:PME:B at 85:10:5 and 80:10:10 compared with PME10 identified that the adding bioethanol can improve the engine performance, but increasing levels of THC and NO [22]. The increasing proportion of PME and bioethanol resulted in the more change of engine performance and the numerous additions of CO_2 and NO [17,21,22]. The use of diesel combined with increasing jatropha oil ethyl ester (JEE) and bioethanol showing that the BSFC was increased and the brake power was decreased, but the release of CO_2 was reduced as the percentage of JEE and bioethanol increased in the mixture [23]. Previous investigation of the blended mixture stability using diesel mixed with WCME at 10 % and bioethanol added from 5 to 20 % indicated that the combining diesel with 10 % WCME and 5 % bioethanol (WCME10B5) had the least phase separation. BTE and BSFC by using WCME10B5 were subtle higher than diesel in all engine speeds; notwithstanding engine performance reduced with increasing bioethanol [24].

Nowadays, the PME10 is becoming an alternative fuel in Thailand as a replacement for conventional fossil diesel, but the engine performance was marginally lower. Most studies have used PME and its blended fuels as for substitution to diesel fuel. Meanwhile, limited work has been done on other PEE. Additionally, another oxygenated reagent such as bioethanol may be suite to use as an additive for fuel mixture. Besides, there is less available information for the comparison among mixture solutions and their effects of performance and emission characteristics. Therefore, the diesel-PEE-bioethanol blended fuel samples applied to LSDI diesel engines would be proposed and presented in a variety of aspects whereas the study of PEE10-bioethanol blends operated with HSDI diesel engines was rarely seen. In subsequence, some other facets have not yet been discovered regarding these issues.

Therefore, the purpose of the present study is to investigate the physical properties as well as the performance and emission characteristics of a HSDI diesel engine operated at a constant speed of 3,000 rpm and different loads using PEE10 and PEE10-bioethanol blends as compared with diesel baseline. The novelty of this study associates to BSFC, BTE as well as gaseous emissions such as THC, NO, CO and other combustion gases such as CO_2 and O. The emitted particulate matter in terms of smoke opacity will also be presented and discussed.

Materials and methods

Arrangements of fuel blends

Reactants, such as diesel, palm oil and bioethanol, were generally purchased from local gas stations, marts and chemical companies. A conventional diesel according to diesel standard specifications (DSS) of the Energy Business Department in Thailand was used throughout the test [10]. Palm oil was oleic based which consisted of free fatty acid, 40.06 % palmitic acid, 4.30 % stearic acid, 40.72 % oleic acid and 12.08 % linoleic acid [11]. Bioethanol was analysis-grade anhydrous ethanol (99.9 % purity). First, PEE was synthesized by transesterification using palm oil reacted with anhydrous ethanol under NaOH catalyst. The mixture of 7 g of NaOH in 217.38 g of water-free bioethanol (99.9 % purity) was reacted with the treated palm oil at the molar ratio of 6:1 in a rounded bottom flask connected with mechanical stirrer at 65 ºC under 800 rpm for 60 min. Purity of PEE was measured by Gas Chromatography (GC) according to EN14103 standard to determine yield of EE. The percentage of PEE was between 98.84 to 99.37 % which was in scope of methyl ester standard specifications (MESS) of this country [10,11].

Next, the producing PEE10 was compared with PME10 whereas the neat PME was produced by palm oil with methanol and same catalyst at the same molar ratio. The PME was then mixed with regular diesel in 10 % by volume to get PME10. After getting the blended fuel, such properties, fuel density (FD) at 15 ºC, kinematic viscosity (KV) at 40 ºC, flash point temperature (FPT), and lower heating value (LHV) were determined, under various ASTM procedures as shown in **Table 1**. The subsequent results prove that the physical properties of PEE and PME, especially FD, KV and FPT, were in scope of MESS [10,11]. However, these properties were higher and the LHV was lower than diesel. PEE10 and PME10 were improved in fuel properties that were in the scope of DSS [10]. The physical properties of both blended fuels were similar to ones reported in [10,11,20]. However, the PEE10 was slightly difference in physical properties compared to those of PME10; the PME10's FD, KV and FPT were increased by 0.15, 1.06 % and 0.68 ºC, respectively, while the LHV was slightly decreased at 0.94 %. Therefore, physical results of PEE10 indicating that it could be used to replace PME10. However, the FD, KV and FPT of PEE10 were increased by 1.55, 29.62 %, 33.68 ºC, respectively while the LHV reduced by 5.21 % as

compared with diesel. To improving PEE10 properties, particularly FD, KV and FPT, this work led PEE10 mixed with bioethanol as studied from the phase diagram of D:PME:B ratio in literatures [18-20] by using emulsification. For investigating homogeneity of PEE10-bioethanol blends, a jacketed glass reactor vessel and an electromagnetic stirrer were applied in controlling the stirring speed, moisture content and temperature on blend stability. PEE10 at the amounts of 95, 90, 85 and 80 % were used to volumetrically mix with bioethanol (5, 10, 15 and 20 %), namely PEE10B5, PEE10B10, PEE10B15 and PEE10B20, respectively.

Table 1 Fuel properties.

Items	**FD** (kg/m^3)	**KV** (mm^2/s)	**FPT** (ºC)	**LHV** (MJ/kg)	**IST**
ASTM	**D1298**	**D445**	**D93**	**D240**	**Ref. [20,24]**
DSS [10]	810 - 870	1.80 - 4.10	52 min	-	-
MESS [10]	860 - 900	3.50 - 5.00	120 min	-	-
Diesel	830	3.09	47.78	44.77	-
Bioethanol	794	1.42	14.08	26.72	-
PEE	870	4.83	173.64	39.89	-
PME	868	4.79	173.11	39.95	-
PME10	842	3.95	80.78	42.84	N/A
PEE10	843	3.98	81.46	42.44	N/A
PEE10B5	839	3.88	20.96	41.07	2 (month)
PEE10B10	833	3.73	17.60	40.72	33 (days)
PEE10B15	829	3.58	14.82	40.03	10 (days)
PEE10B20	822	3.44	12.48	39.25	23 (h)

Finally, the physical properties of PEE10-bioethanol blends were tested under various ASTM procedures (**Table 1**). Besides, investigation of stratification time (IST) was also accomplished as suggested by [20,24]. Because the blend solubility is essential for applying with diesel engines, the rapid separation of the mixed fuels will cause the engine knock. The PEE10-bioethanol mixture compared with PEE10 shows that the FD reduced from 0.52 to 2.51 %, the KV reduced from 3.10 to 14.00 % and the FPT reduced from 60.50 to 84.68 ºC. Importantly, the LHV was lessened from 3.22 to 7.51 % since the CV of anhydrous ethanol and PEE10 was lower than that of diesel, leading to the LHV abatement of PEE10-bioethanol blends. However, the use of 20 % bioethanol mixed with PEE10 had the FD and KV within the scope of the DSS. For investigating IST, the PEE10B5 were separated after 2 months while the adding bioethanol from 10, 15 and 20 % to mix with PEE10, namely PEE10B10, PEE10B15 and PEE10B20, were separated after 33 days, 10 days and 23 h, respectively. Initially, the PEE10B5 and PEE10B10 were acceptable for stability due to the blend solubility for more than a month. The properties of both fuels were in the DSS scope. Principally, the LHV was dropped by 9 % as compared with diesel.

Experimental setup for engine characterizations

The experiments were carried out on 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], while this engine was connected with a generator which can produce the maximum electrical power of 5 kW; the arrangement of the engine set up is shown in **Figure 1**. To increase the engine load, a light-bulb panel, containing arrays of bulbs, was applied with this generator for adjusting electrical loads. While the engine power was transformed into the electrical power, a digital power meter (Richtmass, Model RP-96EN) connecting with a cable clamp sensor (IMARI-CT100/1A) measures the electrical power by converting the signal into an RS485 port with a USB data converter and a hardlock of RP series to processing on a computer. The fluid temperatures, such as atmosphere, coolant, intake and exhaust gas, were measured by K-type thermocouples (FWK-2A-6.35X110) connecting to a temperature data logger (Agilent, Model 34970A Data acquisition) with connection to the computer by using USB converter. Fuel cylinders were used for calculating the fuel consumption (FC) from the number of fuels at 20 mL per time consumption. The air flow rate was measured from a venturi tube and a digital manometer. The exhaust gas emissions were investigated using an exhaust gas analyzer (Cosber, Model KWQ-5 Automotive emission analyzer) by a non-disperse infrared (NDIR) method in analyzing the release of CO_2, CO and THC, and the level of

NO was measured by the electrochemical cell method. A smoke meter (Cosber, Model KYD-6 Opacimeter) was used to measure smoke opacity with the measuring ranges of 0 to18 % for CO_2, 0 to 15 % for CO, 0 to 10,000 ppm for THC, 0 to 5,000 ppm for NO and 0 to 100 % for smoke opacity.

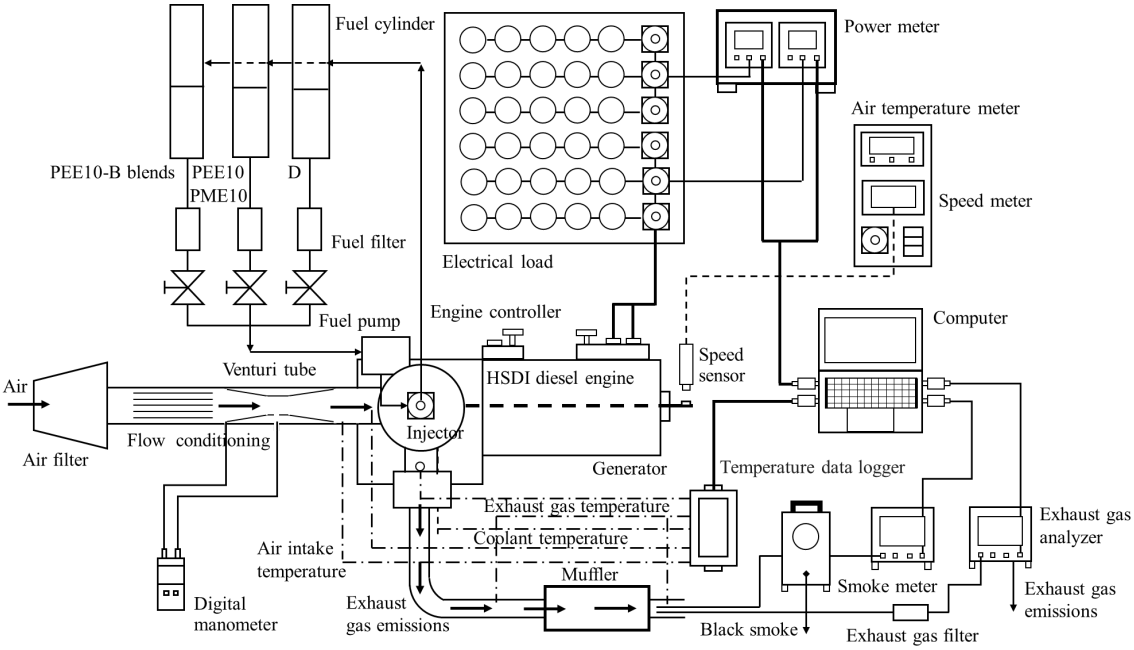

Figure 1 Schematic diagram of the experimental setup.

To study the HSDI engines' operation by using the fuels, diesel, PME10, PEE10 and PEE10-bioethanol blends, the engine was firstly warmed up about 15 min. After the engine was stable, the ambient temperature was controlled at 30 ± 5 ºC and the cooling temperature was limited at 90 ± 5 ºC. Next, engine tests were started up by using diesel. The engine speed was controlled at 3,000 ± 50 rpm. Electrical loads were started from 20 % and later 40, 60, 80 and 100 %, respectively. Fuel volume was fixed at 20 mL to record the change of time. Experimental parameters, such as engine speed, electrical power, air flow rate, FC, temperatures and exhaust gas emissions, were recorded. After the initial run for the 1st fuel, the PME10, PEE10 and blends of PEE10 and bioethanol (PEE10-bioethanol blends), such as PEE10B5, PEE10B10, PEE10B15 and PEE10B20, were investigated, respectively, in the same condition of diesel. Duration of all tests of the engine characteristics was between 100 h, and results were repeated by more than 5 times. Finally, all parameters recorded from using various fuels were calculated in terms of the engine-performance parameters (such as BSFC and BTE) and exhaust-gas products (such as CO_2, NO, CO and THC emissions) [1,10].

Results and discussion

Results of HSDI diesel engine test at a constant speed, 20, 40, 60, 80 and 100 % loads are analyzed in term of brake mean effective pressure (BMEP) to study the changes of engine characterizations. Electrical powers for these loads are of 0.98 ± 0.01, 1.98 ± 0.02, 3.03 ± 0.01, 4.02 ± 0.05 and 4.62 ± 0.06 kW_{ele}, respectively. These are corresponded to BMEP values of 94.83 ± 0.90, 191.10 ± 2.70, 292.79 ± 4.46, 389.95 ± 4.07 and 448.42 ± 3.77 kPa, respectively. Testing the fuels leads to the change of engine characteristics as described below.

Brake specific fuel consumption

Brake specific fuel consumption (BSFC) is calculated based on the amount of FC over electrical production of the generator [1,10], shown in **Figure 2**. The increase in BMEP leads to the decrease of BSFC while the lowest BSFC was at 390 kPa BMEP. At this point, the engine was operating at its optimal condition according to the loaded electrical power consistent to the suitability of fuel usage [1].

Therefore, the comparing parameters of engine characterizations using these fuel blends and diesel in this work is only shown on 390 kPa BMEP load. Using fuels resulted in different behaviors as followed. The comparison between PEE10 and PME10 was first investigated and the results show that the PEE10 consumed more fuels (higher BSFC) than PME10 by 1.19 %. These results are similar to those reported in [15] as this work tested the both fuels at the same engine power and speed. PEE10 had lower CV than PME10 (**Table 1**); the PEE10 had, therefore, a higher FC than PME10 leading to the incremental BSFC. Next, the both fuels are compared with diesel and found that the PEE10 and PME10 led to higher BSFC than diesel, by 7.56 and 6.29 %, respectively. These results are consistent with [8-12] due to the reduction of LHV compared with diesel, leading to the increase in FC and BSFC at the same electrical generation output. Finally, the blends of PEE10 and bioethanol addition comparing with PEE10 and diesel prove that there is the continuous increasing of BSFC, from 2.00 to 13.18 % and 9.71 to 21.73 %, respectively for 5 to 20 % bioethanol. These results are similar to the literatures [19-24] as the LHV of PEE10 and bioethanol was lower than diesel (**Table 1**). While the bioethanol was increasingly blended into PEE10, their blend's CV continuously reduced resulting in the increase of FC and BSFC at the same load.

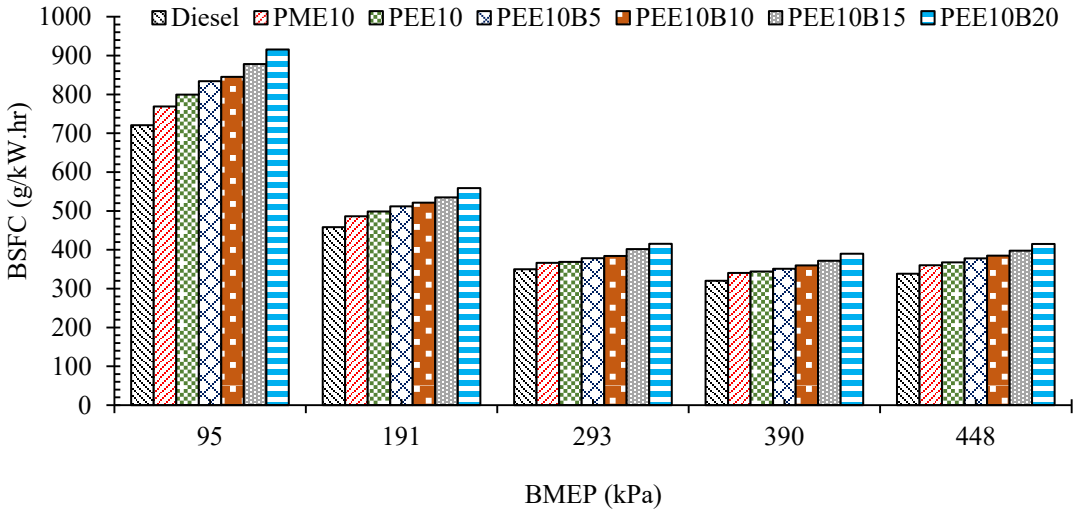

Figure 2 BSFC.

It is also found that the increase of BSFC was by 2 % for PEE10B5 compared to PEE10. These results are similar to the results of PME10B5, diesel mixed with 10 % PME and 5 % bioethanol, published in [22], although the CV of PEE10B5 was lower than PME10B5. Additionally, the use of PEE10B5 resulted in lower BSFC than WCME10B5 as reported in [24] due to more complete combustion in diffusion burning zones [4,5,17]. Moreover, in comparison between the PEE10-bioethanol blends and the diesel-alcohol mixtures reported in [1] tested in same speed and load, the BSFC values were similar and the increase of alcohol, more than 5 %, led to the continuous escalation of BSFC. Notwithstanding, the use of PEE10E5 had lower BSFC than DE5Ea5, diesel mixed with 5 % bioethanol and 5 % ethyl acetate [1]. Because PEE10E5 improved the combustion efficiency in burning zones of diesel engine resulting in more fuel saving than DE5Ea5 [3,17]. Therefore, the use of PEE10E5 seems to be better than WCME10B5 and DE5Ea5 in terms of FC.

Brake thermal efficiency

Brake thermal efficiency (BTE) is analyzed by the output electricity produced per the input energy contained in fuels, which depends on the CV and FC according to engine tests [1,10], as indicated in **Figure 3**. BTE is increased with increasing BMEP, and the best BTE is also at 390 kPa of BMEP as explained in the section of BSFC. BTE from using different fuels is changed as the followings. First, the PEE10 had a lower BTE than PME10 by 0.56 %. These results are similar to the results published in [15] due to its lower LHV than PME10. While both fuels were tested at the same electrical generation output, the FC of PEE10 was a bit higher, resulting in the decrease of BTE [15]. Second, the use of PEE10 and PME10 comparing with diesel confirms that there is the abatement of BTE, by 1.93 and 1.38 %,

respectively. These results are in agreement with [8-12], as both fuels had lower CV than diesel (**Table 1**) leading to the increase of FC at equal electrical power causing the curtailment of BTE. Third, at 390 kPa BMEP, the use of PEE10B5 compared with PEE10 and PME10 had higher BTE by 1.39 and 0.82 %, respectively. These results are consistent with the use of PME10B5 and WCME10B5 in the literatures [22,24], due to a retarded ignition timing of bioethanol than PEE. Higher surrounding temperature for the burning PEE10 within the longer premixed combustion phase was observed. Next, the increasing O molecules of bioethanol combined with 10 % PEE led to more complete combustion in diffusion combustion phase and hence, improving the BTE. Besides, PEE10B5 gave higher BTE than DE5Ea5 presented in [1] due to 10 % PEE addition improved combustion efficiency in burning zones of diesel engine resulting to the increase of BTE [2,3]. On the other hand, the comparison between PEE10B5 with diesel indicates that there is a subtle lower BTE than diesel by 0.57 %. These results are agreeing to those in [21] in that the lower heat of combustion of PEE10 and bioethanol, along with changes in combustion conditions due to comparatively higher viscosity and density of PEE10B5 cause the reduction of BTE. Final, the PEE10 blending with added bioethanol from 10 to 20 % has the curtailment of BTE, continuously dropped from 0.08 to 3.36 % and 2.02 to 5.23 % comparing with PEE10 and diesel, respectively. These results are similar to [1,3,23,24] as the blended bioethanol of more than 10 % led to the CV reduction leading to the incremental BSFC by adding more bioethanol, resulting in the decrease of BTE at the same load. Nevertheless, the use of PEE10-bioethanol mixtures had better BTE than the use of diesel-alcohol blends [1]. These results are clarified by the PEE10 blended with bioethanol improving the combustion mechanism in premixed and diffusion combustion zones resulting in the end of combustion period at the beginning of power stroke. Further adding alcohol to diesel expedited burning rate in premixed combustion area, but ethyl acetate and bioethanol had lower molar enthalpy of vaporization and so they could increase the combustion reaction in the diffusion combustion region leading to the end of combustion period in the middle of power stroke [1,3,17,18]. Summarily, the blends of PEE10 and bioethanol improved BTE rather the mixtures of diesel and alcohol.

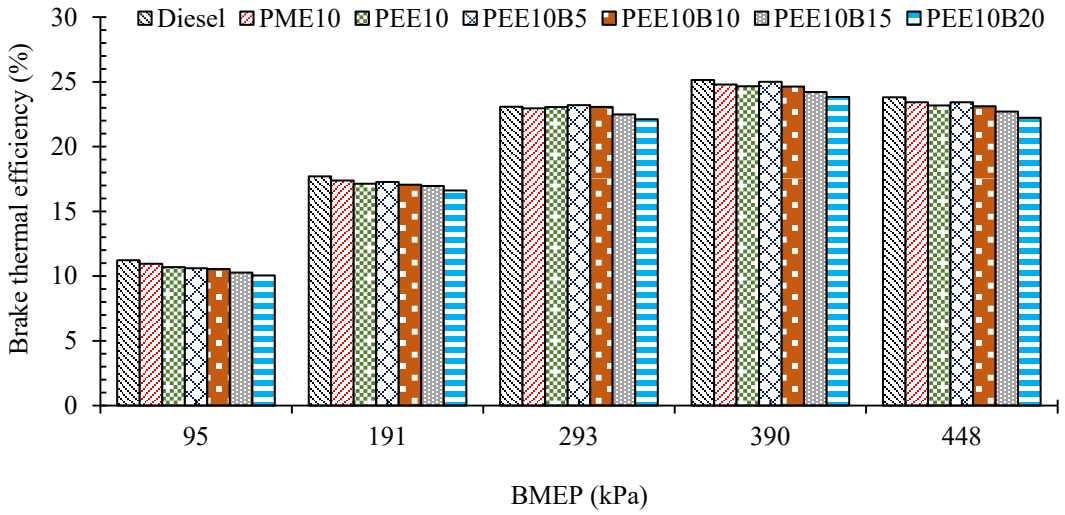

Figure 3 BTE.

Carbon dioxide

Carbon dioxide (CO_2) is produced during the combustion reaction where single carbon molecule is reacted with double O molecules to create CO_2 [10]. The differentiation of CO_2 levels with BMEP by using those fuels was investigated and shown in **Figure 4**. The release rate of CO_2 is firstly enhanced with increasing BMEP. However, the use of fuel blends led to the change of CO_2 levels. In comparison between PEE10 and PME10, the release of CO_2 for PEE10 is lower than PME10 by 2.17 %. This result is in-line with that in [15,16] whereas the higher CO_2 release is by ester that may be attributed to their higher carbon molecules within ester compositions. The chemical structure of PEE has lesser carbon molecule than PME. Therefore, PEE10 emits lower CO_2 concentration than PME10. However, the CO_2 release rate from using PEE10 and PME10 as compared with diesel is proofed that the levels of CO_2

increased for all BMEP, as enlarged to 1.97 and 4.23 %, respectively. These results are consistent with the literatures [6-10]. The empirical formula of both esters shows that there was higher concentration of carbon and O than diesel. These fuels were reacted with O molecules of air surrounding combustion chamber causing the more accretion of CO_2 product. Importantly, the higher BSFC of PEE10 and PME10, indicating in Section 3.1, led to the increase of CO_2 release rate. Moreover, the more concentration of O molecules within both fuels improving the combustion efficiency led to the more complete combustion than diesel resulting in the increased CO_2 level. On the other hand, the increase of bioethanol mixing with PEE10 leads to the decrease of CO_2 release rate.

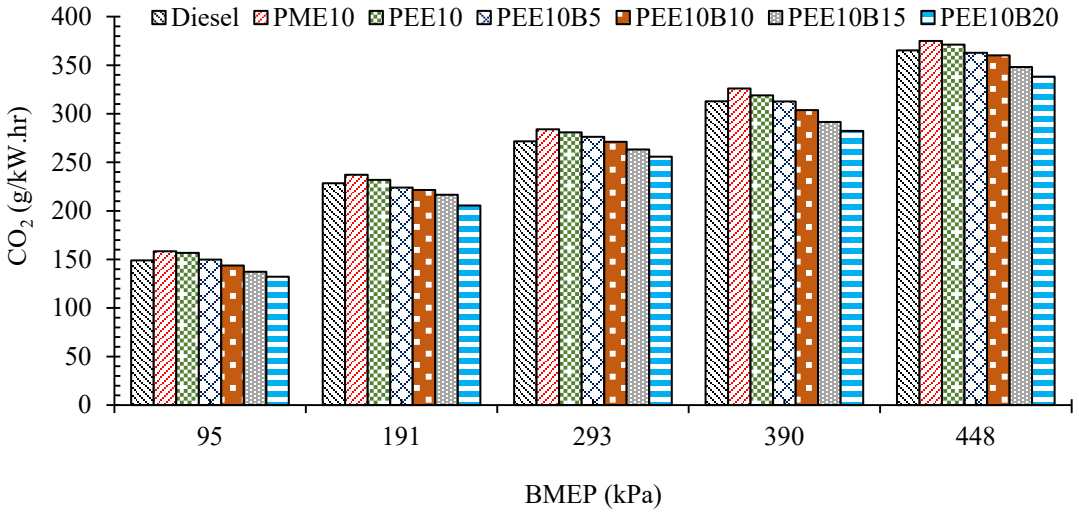

Figure 4 CO_2.

The use of PEE10 with bioethanol addition from 5 to 20 % resulted in the reduction of CO_2 level from 1.95 to 11.46 % and 0.02 to 9.71 % comparing with PEE10 and diesel, respectively. These results are in agreement to those in the references [5,17,23], due to the increment of hydrogen (H) and O concentrations as well as the reduction of carbon (C) molecules in PEE10-bioethanol blends. These fuels reacted with the O molecules of air surrounding in the engine cylinder causing the formation of oxidizing species in term of hydroxyl radical (OH) from bioethanol added. As a result, the level of CO_2 was decreased as increasing bioethanol. These results are contradicted to those reported in [1-3] which used the mixtures of diesel and alcohols leading to the escalation of CO_2 due to more O concentration within the molecular of alcohols reacting with more C molecules. Therefore, the use of PEE10 blended with increasing bioethanol could reduce the CO_2 level better than other alternative fuels.

Nitric oxide

Nitric oxide (NO) is a common designation of nitrogen oxides formed in high temperatures and abundant O concentration [3-6]. NO emissions from burning these fuels and their variations in all MEP are demonstrated in **Figure 5**. The release rate of NO is elevated as the BMEP increased. However, the use of fuel blends is leading to the change of NO level. The comparison between PEE10 and PME10 argues that the PEE10 emits lower NO level than PME10 by 2.83 %. This can be explained that the EE had a lower flame speed which rapidly propagated throughout the combustion chamber than ME resulting the decrease of burning temperature [5,16]. As a result, PEE10 had lower the level of NO than PME10. However, the use of PEE10 and PME10 has higher NO concentration than diesel in all BMEP, as increased by 2.94 and 5.94 %, respectively. These results are similar to the literatures [9,10,13,16] in that the O concentration in PEE10 and PME10 may cause a highly burning reaction in premixed combustion zone by enhancing the flame speed and hence, increasing the combustion temperatures. Also, more O molecules which originate from the fuel blends prolong the premixed combustion duration, providing longer time for NO formation. Contrarily, the increasing bioethanol in PEE10 mixture has changed the phenomena of NO formation. The use of PEE10 blending with bioethanol, incremental from 5 to 20 % leads to the curtailment of NO release rate, as dropped from 3.47 to 17.43 % and 0.63 to 15.00 % as

comparing with PEE10 and diesel, respectively. The obtained results are consistent with the literatures [17,18] by which the reducing molecules of C and increased concentration of H and O from blending PEE10 to greater levels of bioethanol quantities led to a high OH formation, causing the increasing products, particularly gaseous H_2O. Simultaneously, the rapid vaporization rate of bioethanol was strengthened by increasing bioethanol content, resulting in the decrease of auto-ignition temperature. As a result, the flame speed in the premixed combustion phase was reduced leading to the reduction of burning temperature when increasing bioethanol and hence, decreasing the NO level. These results are contradicted to those reported in [20-22] in that the PME10 mixed with bioethanol had higher NO release. This situation may occur as the PME combining with bioethanol contains more O concentration and higher flame speed than PEE blending with bioethanol. Extra O content originated from the burning reaction between the mixtures of PME, bioethanol and surrounding air in the combustion chamber prolongs the burning duration, and it led to the increase of burning temperature and the increasing manifestation of free molecules of nitrogen and O as resulted in the increase of NO formation [16-18].

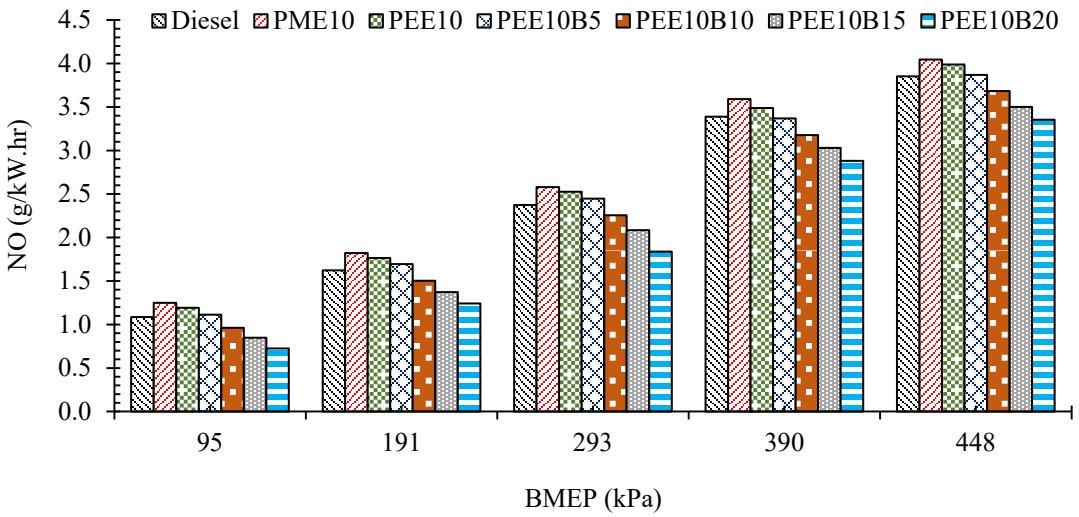

Figure 5 NO emission.

Carbon monoxide

Carbon monoxide (CO) is emitted from incomplete combustion in the fuel-rich mixture combustion [5]. The increase of BMEP leads to the decrease of CO release presenting in **Figure 6**. The lowest CO level occurs at 390 kPa BMEP since the increase of fuel consumption in such condition was appropriate for the amount of air used for the complete combustion [1,5]. Comparing PEE10 with PME10 proves clearly that the PEE10 lowered CO release compared to PME10 by 2.59 %. These results are similar to those in [5-10] with the reason that the EE had lower carbon-hydrogen (C-H) ratio than ME. Therefore, PEE10 had lower C-H ratio than PME10. As a result, the PEE10 had higher air-fuel ratio than PME10 leading to the more complete combustion that reduces CO emission. However, the use of PEE10 and PME10 leads to the reduction of CO release rate as comparing with diesel, as dropped by 7.40 and 4.93 %, respectively. These results are comparable to those in the literatures [9,10]. The concentration of O within the element of PEE10 and PME10 combining with the O molecules from air surrounding was highly burned with hydrocarbon content of both fuels, mainly producing CO_2 and moisture, resulting in the reduction of CO emission. Moreover, the use of PEE10 mixing with increasing bioethanol from 5 to 20 % reveals that the release rate of CO is continuously decreasing with increasing bioethanol, as relieved from 5.24 to 22.49 % and 12.25 to 28.23 %, compared with PEE10 and diesel, respectively. These results are similar to the literatures [17,18,21], because the additional bioethanol in blending to PEE10 led to the decrease of C molecules and the increase of O molecules, promoting more complete combustion and lower CO emission. Besides, the comparison between PEE10-bioethanol blends and PME10-bioethanol mixtures shown in [22] denoted that the declining trend of CO emission for the 2 ingredients was similar. The key findings are that the use of PEE10-bioethanol mixtures had more reduction of CO level than the use of diesel-alcohol blends indicated in [1-3]. This is due to the fact that the PEE10 blended with

bioethanol led to the high O content and the less C-H ratio resulting in the more release of CO_2 than CO emission. On the other hand, the C-H ratio of diesel was higher than PEE10 although it was combined with alcohols. As a result, the levels of CO_2 and CO using the mixtures of diesel and alcohols was higher than the blends of PEE10 and bioethanol [3,17].

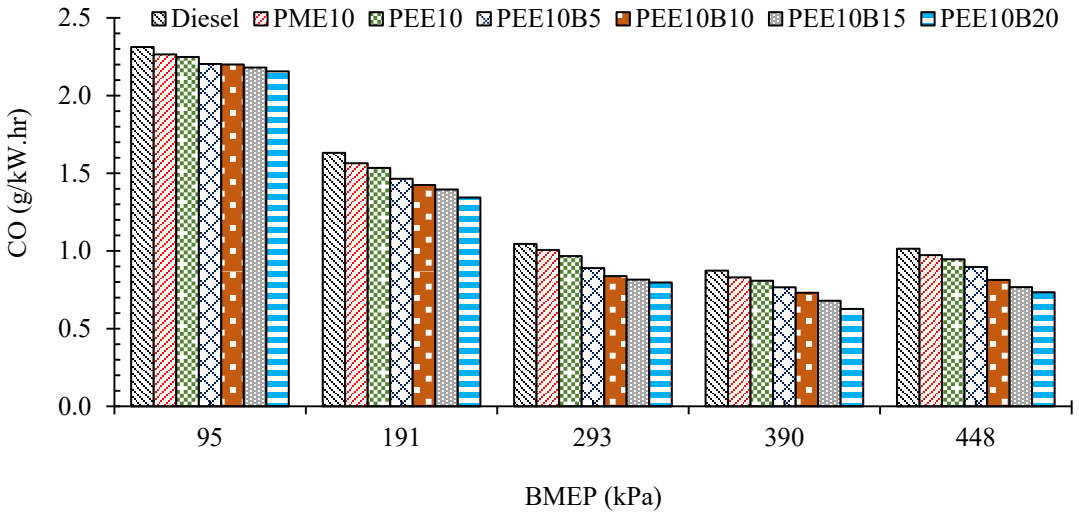

Figure 6 CO emission.

Total unburned hydrocarbons

Total unburned hydrocarbons (THC) are formed by the unburned fuel molecules left in the combustion chamber; their concentrations are dependent on fuel characteristics, sufficient O and incomplete combustion phenomenon [5-8]. **Figure 7** shows the reduced THC with increasing BMEP while the use of fuel blends and diesel is different in release rate of THC. First of all, the comparison between PEE10 and PME10 has shown that the PEE10 lowered the THC emission, by 7.21 %. Similar results have been founded in [15,16] discussing that the reduction of C-H ratio and the addition of O molecules within the composition of PEE10 was higher, leading to more complete combustion than PME10 and consequently reducing THC release. In addition, the THC emission reduction is consistent with the CO emission declination as shown in Section 3.5. Next, the use of PEE10 and PME10 lead to the THC reduction as compared with diesel by 15.29 and 8.71 %, respectively. These results are similar to literatures [5-9], because the high O molecules within element of both fuels combining with O content from air surrounding improved the combustion efficiency in diffusion combustion zone, resulting in the decrease of THC emission. Finally, the release of THC was changed by using PEE10 mixed with increasing bioethanol. THC release was raised by 2.75 to 43.11 % when adding bioethanol from 5 to 20 %, respectively compared to PEE10. Furthermore, the release of THC by using the PEE10-bioethanol mixtures was same as the results of PME10-bioethanol blends [22]. Similar discussion can be founded in [17,22] assuming that the formation of THC primarily originated from the unburned fuel accumulation within various parts of the engine cylinder, particularly areas of ring pistons and chamber walls. The additional bioethanol caused the higher latent heat of vaporization leading to the accretion of accumulating bioethanol vapor within the cylinder, becoming an inferior fuel-O combustion; some fuel vapor was also partially burned with O. As a result, there was a significant accumulation of unburned fuels within various sources of the engine cylinder. These reasons led to the increase of THC level. However, the use of PEE10-bioethanol blends as comparing with diesel shows that there are 2 case studies. In case of PEE10 mixed with bioethanol from 5 to 10 % indicates that the THC level is lower than diesel by 12.95 and 1.70 % using PEE10B5 and PEE10B10, respectively. It is hypothesized by the decrease of C molecules and the increase of O and H molecules within the composition of these fuels were in the ratio of diesel:PEE:bioethanol optimally because of complete combustion condition resulting in lower THC emission than diesel [17,22]. In terms of PEE10B15 and PEE10B20, there are the increase of THC emission, by 5.73 and 21.23 %, respectively compared with diesel. For a reason of increasing

THC from using both fuels, they are discussed in the comparison between PEE10-bioethanol blends and PEE10.

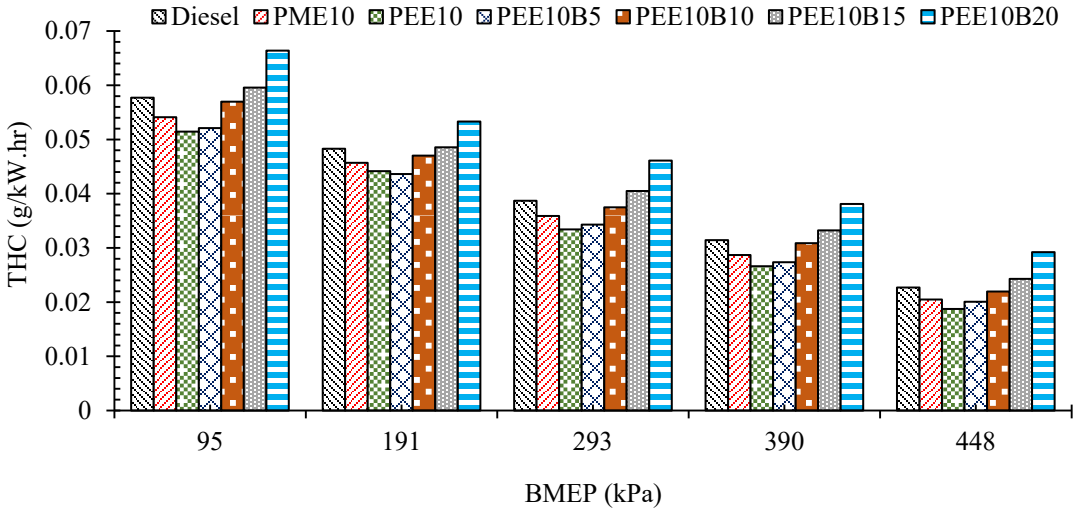

Figure 7 THC emission.

Smoke opacity

Incomplete combustion of fuel usage for diesel engines also results in PM formation that relates to smoke opacity. The smoke opacity is an unintended measure of existence of soot particles in the exhaust [5]. **Figure 8** shows the increase of MEP that leads to the darkened smoke opacity. The increased FC with increasing loads at constant air flow resulted in the more accretion of incomplete combustion [10]. However, the use of fuel blends leads to the abatement of smoke opacity in all BMEP which could be discussed as followed. In comparison between PEE10 and PME10, it clearly proves first that the PEE10 released lesser BS than PME10 by 3.07 %. Mechanism that reduces BS during PEE10 fueling was explained in the same state with the researchers [5,10,15]. The concentration of O within PEE10 element was higher and the C molecules were lower than PME10 leading to more complete combustion in diffusion combustion zone and resulting the reducing smoke opacity than PME10. The use of PEE10 and PME10 are confirmed secondly that there is lower smoke opacity than diesel, by 9.94 and 7.08 %, respectively while these results are agreeing with the literatures [9,10] because of more O molecules within both fuels leading to better combustion in diffusion combustion phase causing the dwindling smoke opacity and decreasing BS emission.

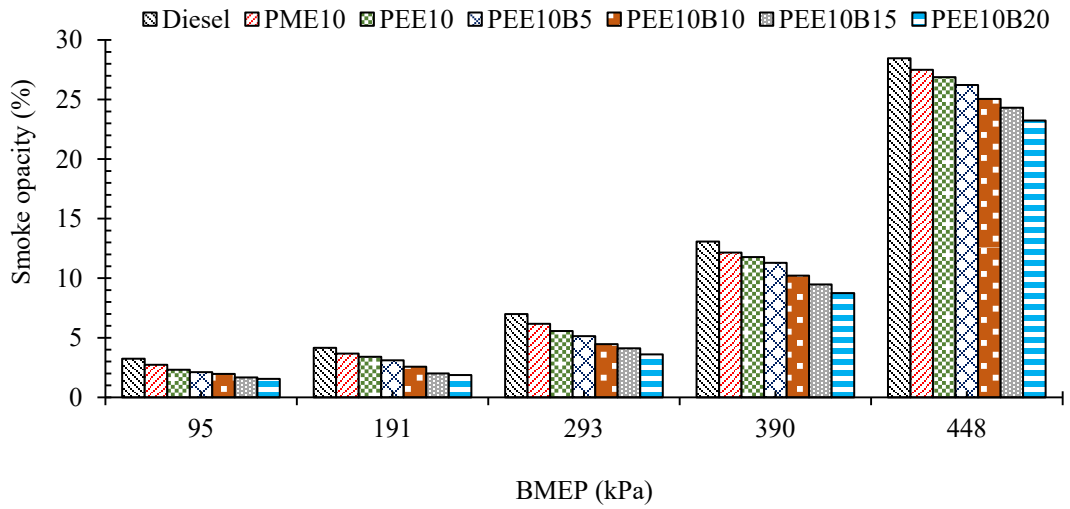

Figure 8 Smoke opacity.

Utterly, bioethanol added to the mixture of PEE10 led to the abatement of smoke opacity continuously. The use of PEE10 blending to bioethanol content increasing from 5 to 20 % reduced the smoke opacity from 4.16 to 25.72 % and 13.68 to 33.10 % compared to PEE10 and diesel, respectively. Therefore, the use of PEE10 blended with increasing bioethanol had lower BS emission than the use of PEE10 and diesel. These results are in-line with those presented in [17-22] due to the fact that the increasing bioethanol in PEE10 mixture led to the lesser C molecules reduction and the more O molecules accretion. This results in the change of combustion phenomena in diffusion zone, which was continuously complete combustion with increasing bioethanol, leading to the lessening BS. Besides, these results correspond to the decrease of CO emission as shown in the section of CO emission. Finally, the comparison between PEE10-bioethanol blends and PME10-bioethanol mixtures proposed in [22] identifies that the BS release from using the PEE10-bioethanol was lowered down. Importantly, the PEE10-bioethanol mixtures had a significantly lower BS emission than the use of diesel-alcohol blends reported in [1]. These 2 cases were hypothesized by the reduction of C-H ratio from using PEE at 10 % mixing with increasing O concentration partly contained in bioethanol leading to the more complete combustion in diffusion combustion zone. As a result, the BS emission was lower than the use of PME10-bioethanol mixtures and diesel-alcohol blends [3,5,17].

Conclusions

Experimental investigation of PEE10 and the blends of PEE10 with bioethanol on the performance and emission characteristics of a HSDI diesel engine at a constant speed and various load can be concluded as follows. First, the use of PEE10 and PME10 blended fuels comparatively shows that the PEE10 performed a subtle lesser engine performance than PME10. The key findings of this study revealed that exhaust emissions: CO_2, NO, CO, THC and BS, by using PEE10 were lower than that of PME10 due to the lesser C-H ratio and more O molecules causing to better complete combustion in the combustion zones of diesel engine. Therefore, the PEE10 could be in consideration for replacement of PME10 in the future. Next, the use of PEE10 and PME10 comparing to diesel in this engine proves that there were the BTE reduction and BSFC increment due to the inferior fuel properties of diesel. Especially, the accretion of fuel density and viscosity and the curtailment of CV led to the increase in FC at the same BMEP, resulting in the BSFC increase and the BTE reduction by 8 and 2 %, respectively. On the other hand, the use of both fuels lowers the levels of exhaust emissions due to more complete combustion than diesel, except for NO.

Lastly, the engine characteristics from using the fuel blends between PEE10 and bioethanol was changed; the PEE10 and 5 % bioethanol blended fuel had higher BTE and lower exhaust emissions than those of PEE10 and PME10. Importantly, the levels of NO and BS were decreased. Contrarily, the increase of bioethanol more than 5 % mixing with PEE10 led to the decrease of BTE and the increase of BSFC compared with PEE10 and diesel. Although the fuel density and viscosity were improved, the LHV was also decreased, leading to the reduction in FC at the same BMEP, resulting in lower engine performance. The main advantage of increasing bioethanol in the blends demonstrates the continuously dwindling exhaust emissions, since more O concentration containing in PEE10 and bioethanol, resulted in more complete combustion. Importantly, the levels of CO_2, NO and BS were continuously reduced.

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