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Emission Characteristics and Engine Performance from Castor Oil Methyl Ester Blends in Diesel Engine under Various Injection Pressures

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ABSTRACT

The use of fuel injection pressure and oxygenated fuels in transport sector are the considerable challenges in making environmentally clean without any modifications in engine design. Therefore, the influence of injection pressure on engine performance and exhaust emission characteristics of common-rail diesel engine has been investigated in this study. The research engine was operated with castor oil blended into the diesel in different percentages at different injection pressures (200, 300, 400 and 500 bar). The results showed that the BSFC increased by 37.2%, 26.8%, 24.53% and 20.31%, from the combustion of COD100, COD10, COD20 and COD30, respectively, and also the thermal efficiency increased from the oxygenated fuels in comparison with diesel under low and high injection pressure. Furthermore, the average reduction of CO and HC emissions was 27.4% and 21.6% from the combustion of castor oil-diesel (COD) blends under 500 bar. The NO_X emissions slightly decreased by 7.3% with increasing the injection pressure up to 500 bar from all COD blends compared to the diesel. It is indicated that the CO_2 emissions increased by 8.6% form the COD blends combustion compared to the diesel with increasing FIP. The PM concentrations gradually decreased with increase the injection pressures by 33.6%, 26.25%, 20.7%, and 17.4% from CO100, CO30D, CO20D and CO10D, respectively.

1. Introduction

An increased excessive usage of fossil fuel in transport sector leads to deteriorate the environment and health due to harmful emissions emitted from diesel engines [1-3]. Therefore, many alternatives such as vegetable/animal fat based biodiesel have been tested by researchers to be one of the solutions in decreasing the exhaust emissions. In addition, manipulating in fuel injection pressure can be a good way to improve the combustion characteristics which result in lower solid and gaseous emissions [4, 5]. The increasing demand on energy, dwindling reserves of fossil fuels, rapid growth in population and increasing pollution encouraged engine researchers to find clean fuels alternative to fossil fuel that can be utilised in diesel engine [6, 7]. It is reported that the animal fat or methyl esters of vegetable oil known as biodiesel because its produced from

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renewable sources, sustainably available bio-fuel and ecological friendly [8]. The pure biodiesel or biodiesel blended into the diesel fuel was used directly in IC engine as a fuel without modifications in the engine [9, 10]. The oxygen-bond in the molecule structure of renewable fuels enhances the combustion characteristics and decreases the exhaust emissions, while slightly increase in the nitrogen oxides (NO_X) concentrations [11, 12]. Gopal *et al.,* [13] examined different biodiesel and biodiesel blends in diesel engine. They found that the increase percentages of biodiesel blends significantly increase the BSFC due to lesser heating value of biodiesel. Furthermore, the results indicated that the hydrocarbon (HC), smoke opacity and carbon monoxide (CO) reduced during combustion of all biodiesel blends in comparison with diesel fuel. In work by Devan *et al.,* [14] determined that adding 15% of biodiesel to the diesel fuel increased the smoke emissions under full engine load and slight improvement in brake thermal efficiency (BTE) compared to the neat biodiesel and other biodiesel blends. Different ratio of oxygenated fuels was blended with diesel fuel to improve the combustion process and exhaust emissions. The oxygen-bond in the renewable fuels is contributing in the complete combustion which result in decreasing emissions of soot, CO, and HC as well as improve the engine performance. Corn Oil Methyl Ester (COME) and its blends into the diesel were tested by Gopinath & Suresh [15] in light duty diesel engine. The results from this study revealed that UBHC, CO_2 and NO_X emissions decreased during combustion of renewable blends in comparison with regular diesel. Previous studies [16, 17] examined the effect of different ratios of biodiesel blends (from 10 to 50%) on emissions characteristics and engine performance. These studies showed that B10, B20, B30, B40, and B50 increased BTE by 1.45%, 2%, 2.2%, 3.5%, and 3.9%, respectively, in the same time increased BSFC by 18%, 12.76% 8.8%, 5.73%, and 1.61%, respectively, compared to the diesel fuel. It is reported that the addition of 40% of biodiesel with diesel fuel improve the engine performance without power loss and decreased the CO, particulate matter (PM) and HC compared to the conventional diesel [18].

For all other fuels, the operation parameters of the engine such as FIP play vital role in improving combustion characteristics and reducing the exhaust emissions [19, 20]. Several methods/techniques have been used to control the PM emissions such as injection strategies (high FIP and delay injection timings) in modern diesel engines. The most important operating parameters in diesel engine is fuel injection pressure due to its significant effect on exhaust emissions and engine performance [21, 22]. Previous studies [23, 24] have been conducted on FIP using several of alternative fuels in direct injection (DI) diesel engines. These studies revealed that combustion rates to be faster with higher injection pressures due to high gas temperatures inside the cylinder. The emissions of CO, HC and smoke deceased from biodiesel-diesel blends with high FIP, while the NO_X emissions increased under various engine speeds [25]. Particulate matter (PM) and CO emission decrease under high fuel injection pressures as demonstrated in work by Zhang *et al.,* [26]. Prior work [27] showed that fuel-air mixing improved under higher fuel injection pressures result in rapid combustion, which in turn reduces the pollutant formation. It is reported that the injecting biodiesel at higher pressures can be resolved the viscosity of biodiesel-diesel blend through improve atomization process which in turn rising dispersion of biodiesel spray [28]. Further understanding of diesel spray characterization (droplet distributions, spray angle, spray structure and spray tip penetration) is considered important to improve the combustion efficiency and decreased the exhaust emissions. Higher fuel injection pressure produce smaller fuel droplets (vaporize rather quickly) compared to the larger droplets that produced from low fuel injection pressure. In addition, Chen *et al.,* [29] and Wang *et al.,* [30] reported that the fuel-air mixture quality improved from high penetration depth of fuel jet and small droplets, which contributes in complete combustion and shorter ignition delays. Both fuel injection timings pressures can help in reducing emissions and combustion noise as well as improve the soot oxidation [31]. Xu *et al.,* [32] reported that the element carbon decreased under increasing injection pressure of 600 bar to 1000 bar by 64% and 50%, respectively, under high engine loads. The maximum feasible decline of soot-NO_X emissions was achieved in work by Fischer and Stein [33] with FIP. It is stated that the oxygen-born fuel plays a significant role in decreasing the rate of soot formation under 200 and 300 MPa of fuel injection pressure. Also, low mixing rate and poor spray atomization under FIP of 100 MPa prohibit the effect of fuel molecule oxygen on soot reduction. The interaction between FIP and fuel molecule oxygen provides a unique opportunity to significant reduction in exhaust emissions and improve the thermal efficiency. Moreover, the effect of FIP and biodiesel blends on the combustion, performance and emissions has not been clearly studied in a DI diesel engine. These topics are interesting and needs further investigated to enrich the literature and to make up for the deficiency of this topics in the literature. The present investigation is focused on the effect of burning castor oil methyl ester injected at various FIP on combustion and emission characteristics in a DI diesel engine. Further, better atomization of castor oil methyl ester resulted from higher fuel injection pressure which may releasing more heat and thereby improve the combustion. The effect of varying FIP on both emissions of soot and NO_X in diesel engine operating by biodiesel was also highlighted.

2. Experiments, Materials and Measurements

2.1 Biodiesel Preparation

The fuel of castor oil was used as a pure fuel (CO100) and blended with diesel fuel in different percentages of 10% (CO10D), 20% (CO20D), and 30% (CO30D) to provide various levels of the emissions. The emissions characteristics and engine performance were measured by tested different blends of castor oil and compared the results with base fuel of CO100 and diesel fuel. Table 1 lists the properties of CO10D, CO20D, CO30D, CO100 and diesel fuel. The main properties in Table 1 are provided from measurement, calculation and suppliers for CO100, diesel fuel and fuel blends [34]. The fuel blends were prepared by mixing different percentages of castor oil methyl ester (20, 40 and 60) with diesel fuel to produce various level of exhaust emission concentration. The main properties of castor oil-diesel blends can be changed with addition castor oil to the diesel. The characteristics of combustion, properties of spray evaporation, and engine emissions could be affect from these changes in the fuel properties.

Table 1
Specifications of CO10D, CO20D, CO30D, CO100 and diesel fuel

Properties	Diesel	CO100	CO10D	CO20D	CO30D
Derived cetane number	52.8	48.6	49.2	49.8	50.8
Viscosity at 40 °C (cSt)	2.574	4.564	3.064	3.546	3.831
Density at 15 °C (kg/m^3)	834.3	883.6	847.8	857.6	869.3
Latent heat of vaporization (kJ/kg)	243	217.2	223	231	238
Thermal conductivity (W/mK)	0.124	0.122	0.126	0.132	0.139
Calorific value (MJ/kg)	44.80	38.46	45.47	46.57	47.63
Sulphur (mg/kg)	10	5	-	-	-
Flash point (°C)	58	70	61	65	68
Total aromatics (wt%)	24.3	0	20.5	18.7	17.3
Lubricity at 60 °C (µm)	312	205.7	307.8	310.4	311.7

2.2 Engine Setup and Tools

For carried-out the experimental evaluation, four cylinders, DI diesel engine was used in this tests as shown in Figure 1. Specifications and details of diesel engine are described in Table 2. Equipment and tools used in this study are presented in the schematic diagram of research engine (Figure 1). An eddy-current dynamometer was coupled with engine to manage and adjusting the engine torque and speed. A Kistler 6125B piezoelectric pressure transducer was used to obtain the in-cylinder pressure with a resolution of 0.5 crank angle. Over 200 consecutive cycles of pressure results was averaged to record and find the pressure trace. The burned mass fraction and heat release is obtained from the data of in-cylinder pressure. Under different engine loads, the dynamometer was calibrated for its efficiency before conducting the experiments. Fuel injection timing and injection pressure were controlled using electronic control unit (ECU). The FIT was kept constant at TDC and four FIP were selected for tested several castor oil-diesel blends.

Exhaust gas analyzer (HPC 500/400) was used during the tests to measure the emissions of CO, HCs, NO_X, and CO_2. TEM Microscopy was used to analyses the particulate morphology. The sample measuring method was explained in the prior work by Fayad *et al.,* [35]. To investigate particulate behavior, the analysis soot morphology parameters were very important. The effect of injection strategies including the FIP on the particulate morphology was interesting for study to reduce the soot formation inside cylinder of diesel engine. Smoke analyzer HPC 500/400 was applied to measure the smoke opacity according to filter exist at lens.

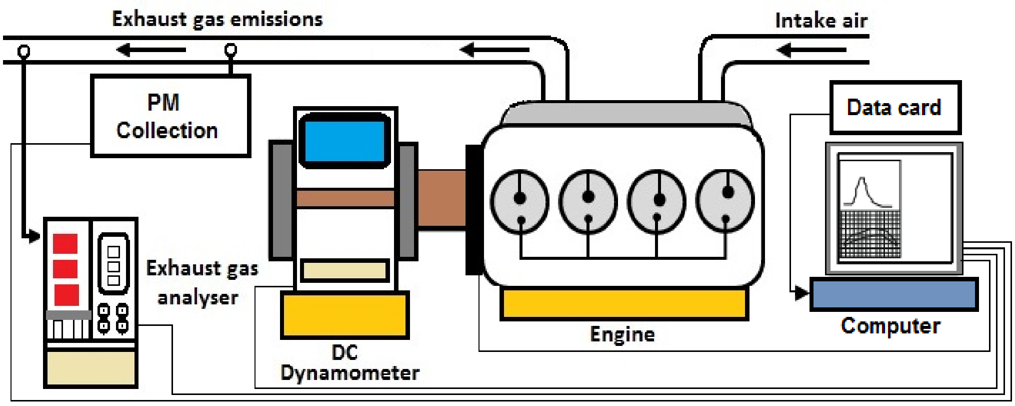

Fig. 1. Experimental setup and tools of engine: Schematic diagram

Table 2
Specifications of engine used

Parameters	Details
Engine type	Diesel engine
Cylinders	4 cylinder
Injection system	Common-rail injection system
Strokes	4 stroke
Bore (mm)	100
Stroke (mm)	125
Rod length (mm)	160
CR (compression ratio)	17.8 : 1
Displacement (cc)	3.6 L
Range of engine speed (rpm)	2000
Range of fuel pressure (bar)	500 - 1500

2.3 Test Procedure and Error Analysis

The engine started with the diesel fuel under variable FIPs (200, 300, 400, and 500 bar) and constant engine speed at 1800 rpm. The second test was carried out with castor oil-diesel (CO100) and then the engine operated with COD blends with the same conditions. Generally, before each test the fuel pipe of the engine cleaned to ensure that no fuel precipitates from the previous test. In the experiments, errors and uncertainties could be occurring from calibrating the equipment, environment, condition, observation, test planning and reading. Regardless of the accuracy and care during the tests, errors will creep into all experiments. Therefore, the analysis of uncertainty is important to prove the experimental accuracy. Many factors during the tests (equipment calibration, reading, environment, measurement result and test planning) can contribute in the uncertainties and experimental errors. Therefore, the uncertainty analysis is essential to prove the accuracy of the experiments. The following equation was used in this study to determine the uncertainty for all tests results [36]:

$$e_R = \left[(\frac{\partial R}{\partial V_1} e_1)^2 + (\frac{\partial R}{\partial V_2} e_2)^2 + \cdots + (\frac{\partial R}{\partial V_n} e_n)^2 \right]^{0.5}$$

Where,
$(\frac{\partial \mathrm{R}}{\partial \mathrm{V}_1})$: The sensitivity for a single variable of the result.

Factors of ei and e_R: Both are represented the uncertainty in the variable of nth and the uncertainty in the results, respectively. The measurement accuracy is listed in Table 3 for the various instruments used in the experiment.

Table 3
Experimental accuracies of various instruments

Measuring equipment	Accuracies %
Engine speed	± 0.98%
Engine torque	± 1.24%
Flow meter of fuel	± 0.50%
Thermocouples	± 0.04%
Sound pressure	± 0.70%
Meter of air flow	± 0.07%
Dynamometer	± 0.90%
Emission concentrations (NO_X, CO, and HC)	± 0.02%
Concentration of PM	± 0.20%

3. Results and Discussion

The variations of BSFC under various FIP for diesel, CO100, CO10D, CO20D and CO30D are presented in Figure 2. The highest brake specific fuel consumption (BSFC) was observed with high amount of fuel injection pressure (500 bar) for all fuels tested as shown in Figure 2. It was observed that the CO100 has the highest BSCF compared to the diesel and COD blends. It could be the lower calorific value of alternative fuels (Table 1) in comparison with diesel fuel is the main reason for this which is in agreement with previous studies [37, 38]. Furthermore, the BSFC increased as the biodiesel content percentage increases in the fuel blend (Figure 2). It is stated in the literature that the BSFC is higher from oxygenated fuel when compared with diesel fuel [39, 40]. In general, it was observed that the oxygenated fuels of castor oil-diesel blends slightly increase the BSFC (lower calorific value) led to high thermal efficiency, as depicted in Figure 3. More castor oil consumed during combustion because of the lowest heating value of castor oil in comparison with diesel fuel and COD blends. The combustion of CO100, CO10D, CO20D and CO30D increase the BSFC by 37.2%, 26.8%, 24.53% and 20.31%, respectively, in comparison with diesel (Figure 2). The higher feeding rate of castor oil during the combustion could be the main reason to produce the same engine torque of diesel fuel. For increasing fuel injection pressure (300, 400 and 500 bar), the BSFC of castor oil blends is less than diesel due to the oxygen concentration in the CO10D, CO20D and CO30D blends molecule which leads to reduce the combustion duration and decrease the BSFC. Furthermore, high injection pressure increase the faster time to reach the maximum pressure which in turn decreases the BSFC in case of castor oil blends compared to the diesel. In addition, the better atomized fuel as well as faster and shorter combustion can enhance pre-combustion under high fuel injection pressures [41].

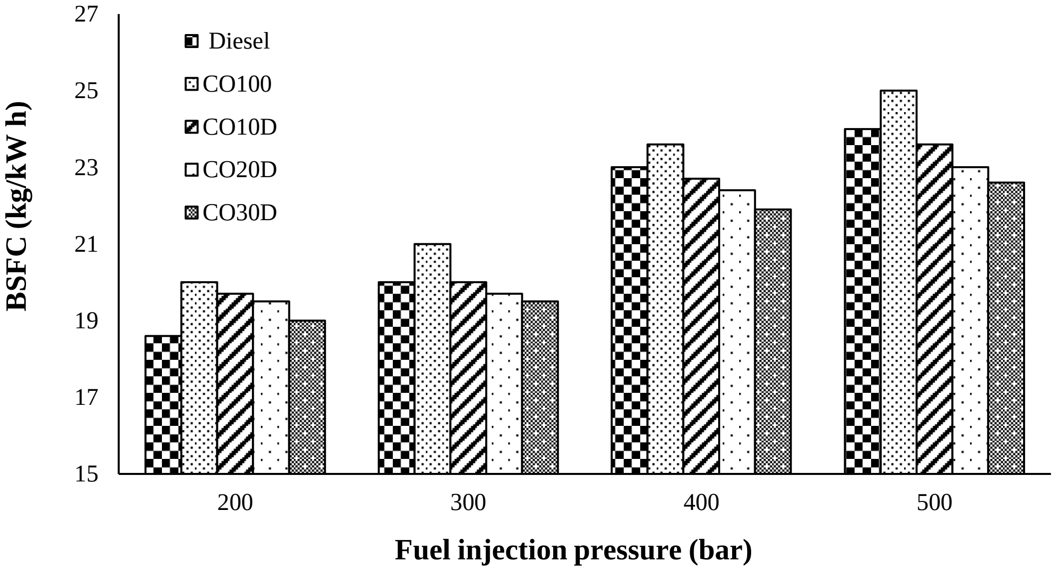

Fig. 2. Influence of various FIP on the BSFC for tests fuels

Figure 3 shows the variations of BTE under various FIP for diesel, CO100, CO10D, CO20D and CO30D. It can be seen that the increasing FIP improve BTE for all fuels tested. This is due to improve the fuel atomization resulted from increasing FIP which leads to improve the combustion process and subsequently producing higher BTE. Previous studies [42, 43] indicated that the thermal efficiency enhanced during oxygenated fuels combustion in comparison with diesel under different operating conditions. The highest BTE generated from the combustion of CO30D compared to the other tested fuels (Figure 3). The blends of CO10D, CO20D and CO30D increase the BTE by 27%, 29% and 31%, respectively, for various injection pressures as depicted in Figure 3. The oxygen-born in COD blends could improve the combustion efficiency; this trend corresponds with results of previous research cited in the Introduction.

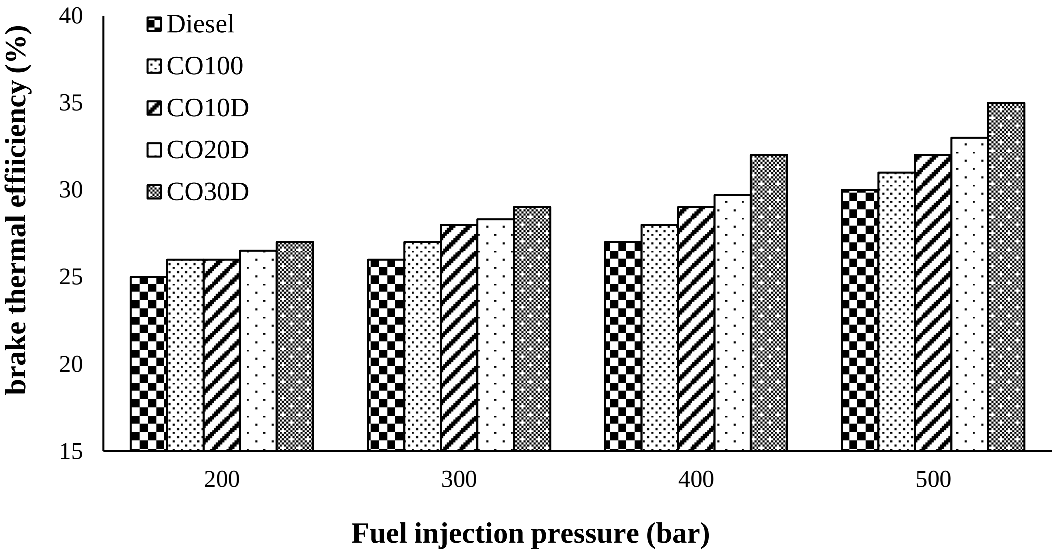

Fig. 3. Influence of various FIP on the BTE for all tests fuels

The effects of various FIPs and oxygenated fuels (CO100, CO10D, CO20D and CO30D) on exhaust emissions concentrations of CO, HC, and NO_X are shown in Figures 4, 5 and 6, respectively. The results showed that less CO, HC and NO_X emissions from the oxygenated fuels compared to the diesel under various FIP. In general, it was observed that significantly less CO, HC emissions emitted from the oxygenated fuels with increasing the FIP in comparison with diesel fuel because of the enhance the fuel atomization as shown in Figure 4 and Figure 5. Another reasons because of the better combustion, smaller droplets and a good fuel-air mixing with high FIP which result in decrease emissions of HC and CO [44]. Besides, moderate level of NO_X emissions from oxygenated fuels than to the diesel, while slightly decrease in the NO_X emissions was found under 500 bar of FIP compared to the low FIP (Figure 6). A large number of studies reported that an improvement in emissions with higher FIP [45-47]. A good fuel-air mixing can be reached with increasing FIP caused complete combustion of the smaller droplets which result in lower concentration of CO emissions. For all FIPs, it can be observed that CO emissions decreased by 32.40%, 23.76% and 18.95% from the combustion of CO10D, CO20D and CO30D, respectively, in comparison with diesel fuel (Figure 4). These results occurred due to the fact that that more oxygen available for fuel burning and less time available for CO formation. It is reported that lowest CO emissions are produced from the renewable fuels that content oxygen-bond in its properties [40, 48]. Previous study [49] examined that the mixing biodiesel (waste cooking oil) into the diesel fuel in diesel engine at six FIP (170 bar, 180 bar, 190 bar, 200 bar, 210 bar and 220 bar). They found that the BTE increased, while CO and smoke decreased with increasing FIP up to 210 bar.

The formation of HC produced from the partially fuel burned or completely unburned fuel inside combustion process. Figure 5 shows that HC decreased from the oxygenated fuel than to the diesel fuel for all conditions of FIP. The concentration of HC decreased with increasing the castor oil percentage into the diesel fuel. This could be due to the presence of oxygen molecules in castor oil leading to the more complete combustion. For all FIPs, the results showed that the CO100 combustion decreases the HC concentrations by 28% in comparison with diesel fuel. This trend was reported in the prior works that the rise oxygen-bond in the fuel blend contributing in provide more complete combustion, which in turn producing lower level of HC emission. Furthermore, the concentration of HC decreased more from the combustion of CO30D, CO20D and CO10D by 28.50%, 19.84%, 9.21% and 13.26% in comparison with those emitted from diesel, respectively. According to the results, it is clear that the minimum level of HC concentrations was under 500 bar of FIP condition as depicted in Figure 6. The excellent mixing between fuel and inside the combustion chamber is the reason to justify that. Therefore, the concentration of HC was lower compared to the low condition of FIP. The current findings of HC in the current study are compatible with previous work by Szybist *et al.,* [50].

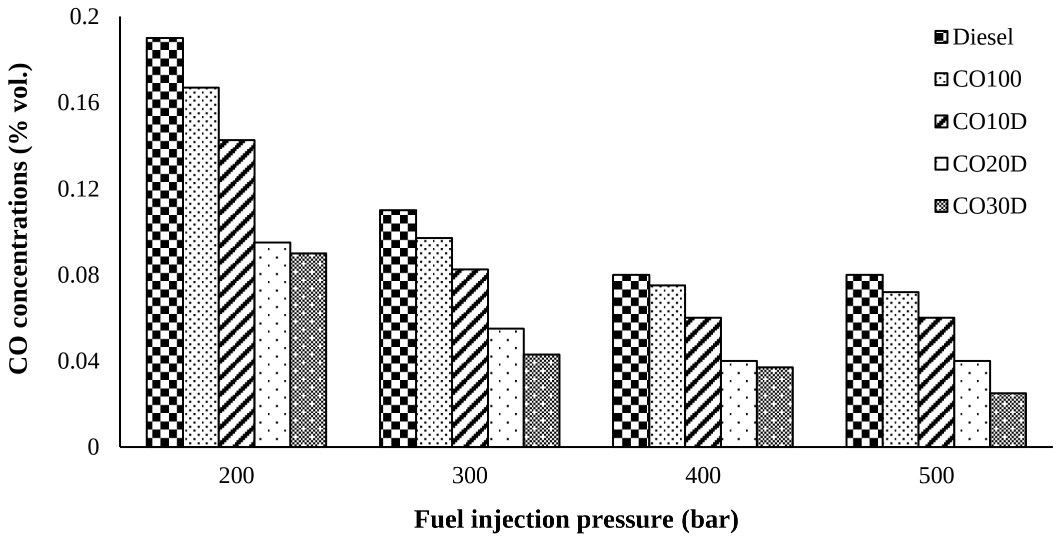

Fig. 4. Influence of various FIP on the CO concentrations for all tests fuels

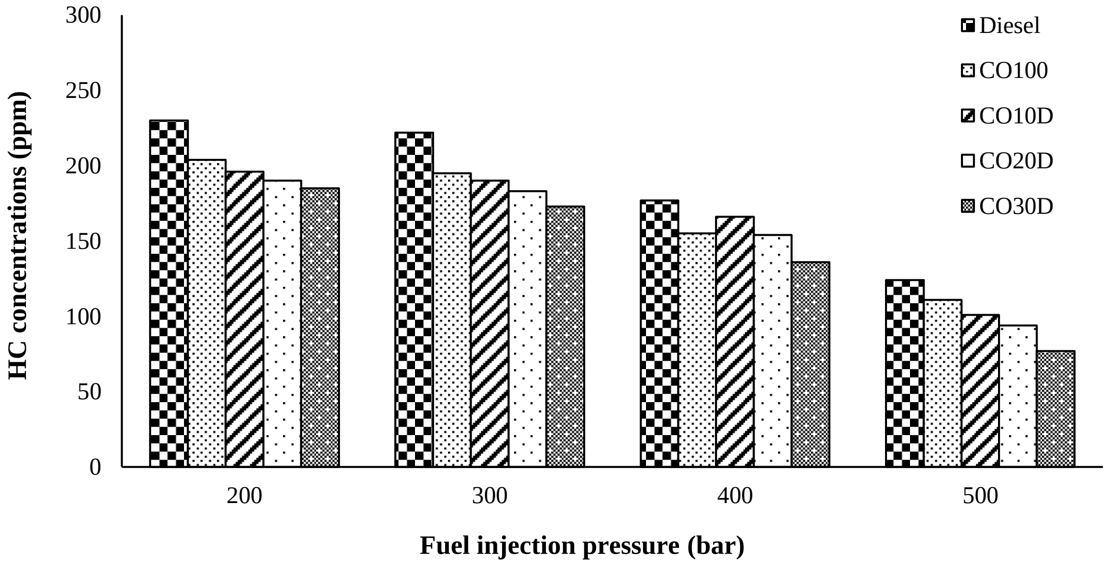

Fig. 5. Influence of various FIP on the HC concentrations for all tests fuels

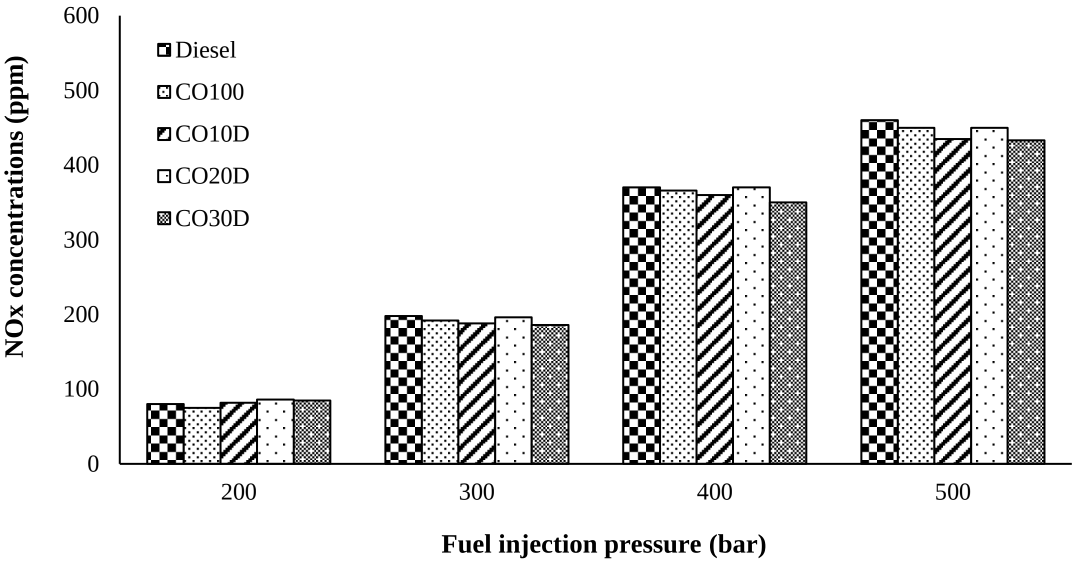

Fig. 6. Influence of various FIP on the NO_X concentrations for all tests fuels

The complete combustion of fuel is indicated from the high production of CO_2 emissions. The key component in the global warming is CO_2. An opposite behavior of CO_2 emissions concentration when contrasted with CO emission concentrations due to the enhancement in the combustion process [51]. The level of CO concentrations from the oxygenated fuels (castor oil blends) and various FIPs are given in Figure 7. The level of CO_2 emissions concentration increased with increasing the FIP for all fuel mixtures. A higher cylinder temperature produced from the combustion of castor oil blends with increasing FIP because of the higher bulk modulus of oxygenated blends and increases the oxidation process between oxygen molecules and carbon [6], which result in higher level of CO_2 emissions. Another reason may be because of the more fuel injected into the combustion cycle and increasing the oxidation rates and combustion temperature. According to the results, it can be seen that the CO_2 emissions increased during the combustion of CO100, CO30D, CO20D and CO10D in comparison with diesel fuel under various FIP. The key reasons to justify that are the oxygen-bond in the castor oil blends and increasing the FIP leading to improve the combustion process which result in increased the CO_2 emissions. Figure 7 shows that the increasing castor oil proportion leads to increasing the CO_2 emissions formation in the exhaust. It is reported that the fuel's carbon content per unit energy can be determine the CO_2 emissions [6, 52]. For all conditions of FIP, it can be noticed that CO_2 increased by 20.13%, 14.22%, 6.32%, and 2.87% from the combustion of CO100, CO30D, CO20D and CO10D, respectively, compared to the diesel fuel. Previous study [53] reported that effective combustion resulted from higher level of CO_2 concentrations of biodiesel due to the molecule structure of oxygen-bond in the biodiesel.

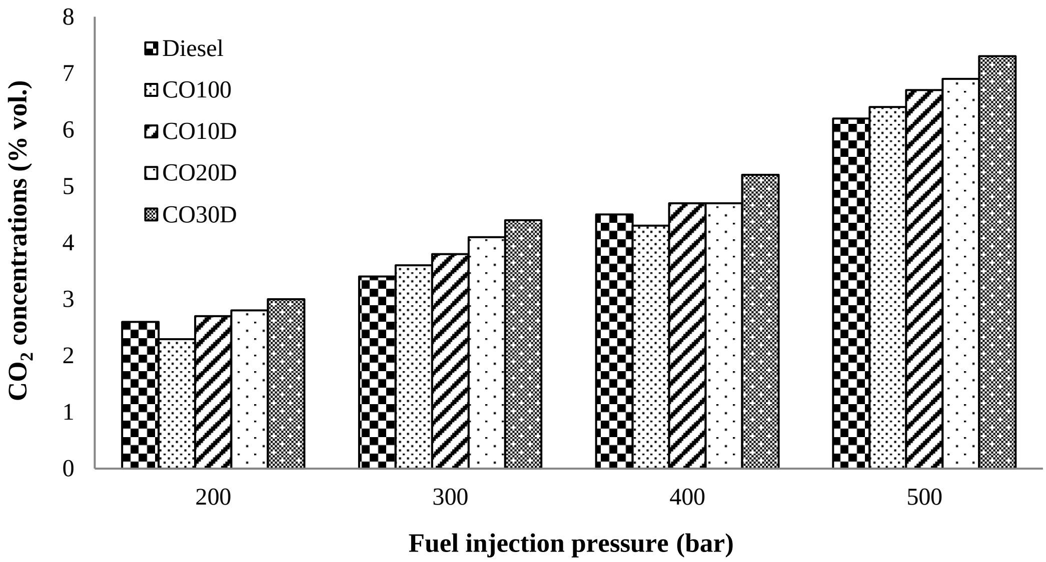

Fig. 7. Influence of various FIP on the CO_2 concentrations for all tests fuels

The effects of FIP and castor oil blends on concentrations level of particulate matter are shown in Figure 8. It can be noticed that particle number concentration in the exhaust reduced with increasing FIP from 200 bar to 500 bar for all fuel blends. The better fuel-air mixing, improve fuel atomization (smaller fuel droplets) and high combustion temperature with high FIP are the main reasons for PM reduction. Besides, improve air entrainment and better spray atomization are mainly attributing to this behavior. It is reported that increasing FIP up to 600 bar leads to lower PM formation during the fuel combustion [54]. The effect of FIP on soot emissions was studied by Pickett and Siebers [55] in diesel that constant volume combustion vessel and fuel jets injected into combustion cycle with high pressure and temperature. The results revealed that the particulate emissions decreased with increasing FIP due to the fuel-air premixing that occurred upstream of the lift off length, low amount of air entrainment and a decline in the residence time of particulates. As pointed out in Figure 8, the PM concentrations emitted from CO100, CO30D, CO20D and CO10D significantly decreased by 33.6%, 26.25, 20.7, and 17.4%, compared to the particulate emitted from conventional diesel fuel (Figure 8). High content of oxygen-born into the COD blends properties leads to decrease the available time to form the PM and increase the PM oxidation are the main reason to justify the PM reduction. Numerous studies [9, 56] reported that the PM can be reached the maximum reduction from the oxygenated fuels under different engine operating conditions. The trend of distribution area shifts towards relatively smaller particles of PM with increasing FIP as presented in Figure 8. The mixing of fuel droplets with surrounding air improved with increasing FIP which result in lower PM concentrations and inhibited particulates formation. It is documented that soot formation and PM emissions significantly decreased with use high FIP in diesel engine [57, 58].

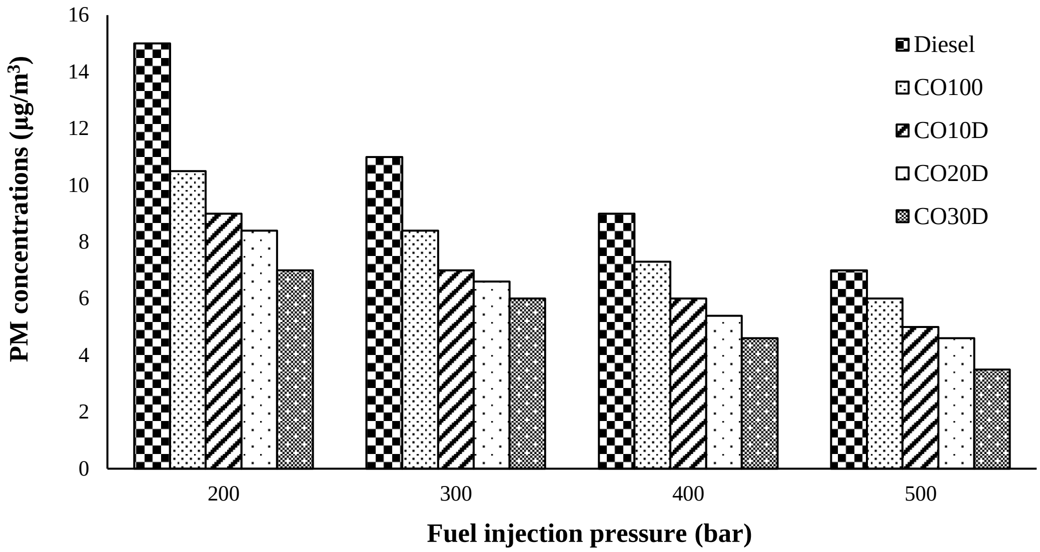

Fig. 8. Influence of various FIP on the PM concentration for tests fuels

4. Conclusions

The effect of FIPs and castor oil-diesel blends on the emissions characteristics and PM concentrations of diesel engine were investigated in this study. The following conclusions can be drawn based on the results of the current study:

i. It was observed that the high FIP increase the engine performance when the engine was fueled with castor oil or its blends in comparison with conventional diesel fuel.
ii. It was found that the increasing the proportion of castor oil into the diesel leads to improve the BTE efficiency by 31% compared to the diesel for different FIP.
iii. The results indicated that the oxygen-bond in the castor oil blends contributed in significant decrease in CO and HC emissions under various FIPs.
iv. In terms of FIP, it was observed that NO_X emissions slightly decreased by 7.3% with 500 bar from the combustion of COD blends compared to the diesel.
v. The CO_2 emissions increased from the combustion of oxygenated fuels (CO100, CO30D, CO20D and CO10D) when compared to the diesel for the same condition of the FIP.
vi. The main conclusion from this study revealed that the significant decrease in the PM concentrations was determined with high FIP compared to the low FIP for all fuels studied.
vii. It can be concluded that the combustion of CO100, CO30D, CO20D and CO10D have beneficial in decrease the PM concentrations by 33.6%, 26.25, 20.7, and 17.4%, respectively, in comparison with diesel fuel.
viii. Most notably, it was obtained that the highest decrease in the PM and gaseous emissions from the interaction between castor oil blends injection pressure.
ix. It is recommended from the present paper that the interaction between different alcohol-biodiesel-diesel blends and injection strategies could be interesting focus and will be addressed in next work.

5. Conflict of interests

The author confirms and declares that there is no conflict of interests regarding the publication of this paper.

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