PERFORMANCE, EMISSION, AND COMBUSTION ANALYSIS OF A COMPRESSION IGNITION ENGINE USING BIOFUEL BLENDS

by

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This study aimed to investigate the effects on performance, emission, and combustion characteristics of adding biodiesel and bioethanol to diesel fuel. Diesel fuel and blend fuels were tested in a water-cooled compression ignition engine with direct injection. Test results showed that brake specific fuel consumption and volumetric efficiency increased by about 30.6% and 3.7%, respectively, with the addition of bioethanol to binary blend fuels. The results of the blend fuel's combustion analysis were similar to the diesel fuel's results. Bioethanol increased maximal in-cylinder pressure compared to biodiesel and diesel fuel at both 1400 rpm and 2800 rpm. Emissions of CO increased by an amount of about 80% for fuels containing a high level of bioethanol when compared to CO emissions for diesel fuel. Using biodiesel, NO emissions increased by an average of 31.3%, HC emissions decreased by an average of 39.25%, and smoke opacity decreased by an average of 6.5% when compared with diesel fuel. In addition, when using bioethanol, NO emissions and smoke opacity decreased by 55% and 17% on average, respectively, and HC emissions increased by an average of 53% compared with diesel fuel.

Key words: *safflower oil, bioethanol, biodiesel, combustion characteristics, engine performance, exhausts emissions*

Introduction

Over the last few years, bio-fuels have been the most preferred alternative fuels, especially for engines. They have similar features to fossil fuels, but are renewable and reduce pollution emissions. Recent studies have focused on biodiesel as an alternative to diesel fuel with interest increasing day by day due to their better fuel consumption. Biodiesel can be produced from both animal fats and vegetable oils, or by using their waste products. Numerous research studies have found that biodiesel generally improves exhaust emissions such as CO, HC, and soot due to its oxygen content, notwithstanding that it has a negative effect on NO_x (total nitrogen oxides) emission and engine performance. Bioethanol can be produced from sugar beet, corn, wheat, and sugar cane. Although it is used commonly in spark ignition en-

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gines, researchers have shown that it also can be used mixed with diesel fuel in Diesel engines. The high octane number of bioethanol restricts the usage of a high rate of bioethanol in Diesel engines.

Biodiesel has a higher viscosity which causes the non-atomization of injected fuel and makes the cold flow properties of the fuel worse. In addition, the lower calorific value of biodiesel is also a significant disadvantage for its fuel properties. Nevertheless, research on biodiesel has increased due to the higher cetane number (CN) of biodiesel and its usability in a Diesel engine with little or no-modification in the engine [1, 2]. On the other hand, some properties of bioethanol such as higher oxygen content and lower viscosity may improve NO_x emissions in Diesel engines and the atomization of injected fuel [2, 3]. The addition of bioethanol to biodiesel-diesel fuel blends decreases the CN, and its lower density causes non-homogeneous fuel blends.

Some current studies about bioethanol-biodiesel-diesel fuel blends in the literature are presented here. Tse *et al.* [4] investigated the combustion characteristics and trade-off relations among particulate mass (PM), particulate number (PN) concentrations, and NO_x from a Diesel engine fueled with diesel, biodiesel from waste cooking oil, and diesel-biodiesel-ethanol blends. Their results showed that the in-cylinder pressure and peak heat release rate of diesel-biodiesel-ethanol blends were comparatively higher than that of diesel and biodiesel. However, ethanol in diesel-biodiesel-ethanol blends has an added advantage of reducing NO_x emissions, leading to lower PM, PN, and NO_x than diesel, and lower PN and NO_x but higher PM than biodiesel. Khoobbakht *et al.* [5] prepared fuel blends of diesel-ethanol-biodiesel produced from waste cooking oil, and they demonstrated the optimization of the exhaust emissions from a Diesel engine using response surface methodology. Test results showed that biodiesel and ethanol reduced CO, HC, NO_x, and smoke opacity and increased CO_2. Shahir *et al.* [6] made a review of the effect on performance and emissions of diesel-biodiesel-ethanol/bioethanol blends. According to the results of the review, the use of these blends in Diesel engine increased the brake specific fuel consumption (BSFC). Beside PM, soot, smoke, and HC emissions were also greatly reduced. The CO, CO_2 and the unregulated emissions, especially the carbonyl compounds, remained almost the same as from the diesel fuel exhaust. When the NO_x emissions were analyzed, they stated that although some of the researchers had identified a reduction in these, most of the results from various investigators and scientists showed that they increased by using these blends. Mofijur *et al.* [7] also worked on a review of the role of ethanol-biodiesel-diesel blends on the reduction of diesel emissions. The conclusions of this review showed that ethanol-biodiesel-diesel blends reduce the PM, HC, and CO emissions, but that these blends increase NO_x and CO_2 emissions. Sastry *et al.* [8] investigated the effect on performance and emission parameters of diesel-ethanol-fish oil biodiesel blends at different injection pressures. Test results showed that BSFC increases by using blends with ethanol as an additive. However, this decreases with an increase in injection pressure. The volumetric efficiency values of blend fuels are more as compared to diesel fuel. The CO emissions and smoke density significantly decreased by using blended fuels with ethanol as additive and were found to decrease with an increase in injection pressure. The NO_x emissions were decreased by the addition of ethanol. However, they increased with the injection pressure. Alptekin *et al.* [2] tested the effect on engine performance, combustion characteristics, and exhaust emissions of using waste animal fat biodiesels-bioethanol-diesel fuel blends. In their study, the biodiesels were produced from waste chicken fat and waste fleshing oil. They mixed bioethanol (5, 10, and 20%) with biodiesel-diesel fuel blends which contained 20% biodiesel. According to results of their study, BSFC values increased with increasing bioethanol concentration in the fuel blends. The start of combustion (SoC) values and start of fuel injection timings was retarded when using bioethanol. While CO_2 emission values were decreased by using bioethanol, CO and NO_x emissions followed a different trend due to the engine load.

The biofuels used for this study were produced from regional feedstocks which used biodiesel from the Remzibey safflower and bioethanol from sugar beet. According to literature survey, biodiesel is disadvantageous compared to diesel fuel in terms of fuel properties such as density, viscosity, and cold filter plugging point. In addition, the use of biodiesel increases NO_x emissions considerably. Bioethanol was added to the diesel fuel-biodiesel blends for reduce these negative effects of biodiesel and investigated the effects on performance and also combustion characteristics of the addition bioethanol.

Materials and methods

Test fuels

Commercial Euro diesel (cED) purchased from a local petrol station was used as the primary fuel in tests. The biodiesel used in this study was produced from safflower seed oil via the transesterification method [9] in the biodiesel production plant of Selcuk University, Konya, Turkey. The bioethanol added to the biodiesel-cED blends was provided by the Cumra Sugar Integrated Plant, Konya, Turkey, and was produced from sugar beet. The prepared test fuels were coded as cED, safflower oil biodiesel (SB), bioethanol (BE), SB3 (97% cED, 3% SB), SB20 (80% cED, 20% SB), SB3BE5 (92% cED, 3% SB, 5% BE), SB3BE10 (87% cED, 3% SB, 10% BE), SB20BE5 (75% cED, 20% SB, 5% BE), and SB20BE10 (70% cED, 20% SB, 10% BE). The properties of the test fuels are given in tab. 1. The phase separations of blended fuels, which were stored in glass beakers, were observed over three months. An arresting dissociation in the fuels was not seen. Even so, the blended fuels were mixed for homogenizing before each test. The properties of the test fuels were determined in the Energy Institute of the Marmara Research Center which is accredited by The Scientific and Technological Research Council of Turkey.

Table 1. Fuel properties of test fuels

Fuels	Density, at 15 °C	Viscosity, at 40 °C	Lower heating value	Cetane number
Analysis method	EN ISO 12185	EN ISO 3104	ASTM D 240	EN ISO 5165
cED	834.5	2.794	43.14	55.2
SB3	835.8	2.834	42.86	55.2
SB3BE5	833.1	2.61	42.12	53.8
SB3BE10	830.6	2.534	41.38	51
SB20	844.4	3.02	42.1	55.5
SB20BE5	841.7	2.917	41.35	54.1
SB20BE10	839	2.836	40.61	51.4

Experimental apparatus

The specifications of the engine used in tests are given in tab. 2. Properties of hydraulic dynamometer used for adjusting engine load, properties of pressure sensor, encoder, and amplifier used for combustion analysis, properties of emission analyzer used for exhaust gas analysis, properties of load-cell used for engine torque and fuel consumption were given in tab. 3. The schematic diagram of the experimental set-up is shown in fig. 1.

Table 2. Specification of test engine

Model	Antor 3LD510
Engine type	4-stroke direct injection
Cylinder number	1
Total cylinder volume, [cm^3]	510
Diameter × stroke, [mm]	85 × 90
Compression rate	17.5:1
Maximum engine speed, [rpm]	3300
Maximum engine torque, [Nm]	32.8
Maximum engine power, [kW]	9
Injector pressure, [bar]	190

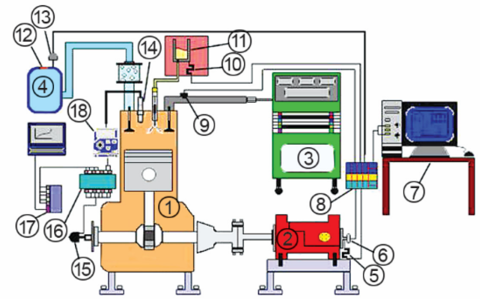

Figure 1. Schematic diagram of the experiment set-up: *1 – test engine, 2 – HYD dynamometer, 3 – exhaust gas analyzer, 4 – air balance tank, 5 – load cell for torque, 6 – speed sensor, 7 – load controller, 8 – data acquisition, 9 – PT100 for exhaust gas temperature, 10 – load cell for fuel consumption, 11 – fuel tank, 12 – orifices plate, 13 - differential pressure transducer, 14 – in-cylinder pressure sensor, 15 – encoder, 16 – combustion analyzer, 17 – data acquisition, 18 - amplifier*

Table 3. Features of measure equipments

<table>
<tr><td colspan="3">Hydraulic dynamometer</td><td colspan="6">Pressure sensor (Kistler – 6052C)</td></tr>
<tr><td>Mark – model</td><td>Range of speed [rpm]</td><td>Range of torque [Nm]</td><td colspan="2">Type</td><td colspan="2">Range of measure [bar]</td><td colspan="2">Working temperature [°C]</td></tr>
<tr><td>Net fren-NF150</td><td>0-6500</td><td>0-450</td><td colspan="2">Piezoelektrik</td><td colspan="2">0-250</td><td colspan="2">-20-350</td></tr>
<tr><td colspan="3">Load cell for torque</td><td colspan="6">Amplifier (Kistler – 5018A)</td></tr>
<tr><td>Mark – model</td><td colspan="2">Range of weight [kg]</td><td colspan="2">Channel number / working temp. [°C]</td><td colspan="2">Range of measure [pC]</td><td colspan="2">Output signal [v]/ Frekans [kHz]</td></tr>
<tr><td>CAS – SBA 200L</td><td colspan="2">0-200</td><td colspan="2">1/0-50</td><td colspan="2">2-2200000</td><td colspan="2">–10-10/0-200</td></tr>
<tr><td colspan="3">Load cell for fuel consumption</td><td colspan="6">Encoder</td></tr>
<tr><td>Mark – model</td><td colspan="2">Range of weight [kg]</td><td colspan="2">Mark – model</td><td colspan="2">Working temp. [°C]</td><td colspan="2">Range of measure [rpm]</td></tr>
<tr><td>CAS – BCL-1L</td><td colspan="2">0-3</td><td colspan="2">Kübler – Sendix 5000</td><td colspan="2">–40-85</td><td colspan="2">0-12000</td></tr>
<tr><td colspan="3">Differential pressure transmitter for air consumption</td><td colspan="6">Gas analyzer</td></tr>
<tr><td>Mark – model</td><td colspan="2">Range of weight [kg]</td><td>CO (v/v)</td><td colspan="2">HC [ppm]</td><td colspan="2">NO [ppm]</td><td>Smoke opacity [%]</td></tr>
<tr><td>BD-DMD 341</td><td colspan="2">0-1000</td><td>0-10</td><td colspan="2">0-9999</td><td colspan="2">0-5000</td><td>0-100</td></tr>
</table>

Experimental method

The load capacity of the dynamometer used for the tests is too high for the test engine and it is almost impossible to stabilize the engine load. Therefore, engine tests were performed at different engine speeds (1000 rpm to 3000 rpm, ranges of 200 rpm) at full throttle condition. In-cylinder pressure values of a minimum of 50 engine cycles at a precision of 1° crank angle (CA) were recorded by a computer using the data-logger. They were determined by using single-zone combustion model in the given equation and Savitzky-Golay filter method [10].

$$\frac{\mathrm{d}Q_{\mathrm{net}}}{\mathrm{d}\theta}=\frac{\gamma}{\gamma-1}P\frac{\mathrm{d}V}{\mathrm{d}\theta}+\frac{\gamma}{\gamma-1}V\frac{\mathrm{d}P}{\mathrm{d}\theta}+Q_{\mathrm{w}}$$

where γ is the ratio of specific heats, θ – the CA, P – the cylinder gas pressure, V – the cylinder volume, Q_{w} – the heat transfer from the cylinder wall in the above equation used for the calculation of heat release rate.

Accuracies of all the measurements and the uncertainties in the calculated results are shown in tab. 4.

Table 4. Accuracies of the measurements and the uncertainties in the calculated results

Measured data	Accuracy	Uncertainty
Fuel weight [g]	±0.01	–
Engine speed [rpm]	±1%	–
Load [g]	±1	–
Engine torque [Nm]	–	±0.36%
Engine power [kW]	–	±0.6%
Fuel consumption [$\mathrm{gs^{-1}}$]	–	±0.41%
BSFC [$\mathrm{gkW^{-1}h^{-1}}$]	–	±0.51
BTE [%]	–	±0.53
CO [$\mathrm{vv^{-1}}$]	±0.001	–
HC [$\mathrm{vv^{-1}}$]	±1	–
NO [ppm]	±1	–
Smoke opacity [%]	±0.01	–
T_{ex} [°C]	±2	–

Result and discussion

Engine performance

Figure 2 shows that BSFC and brake thermal efficiency (BTE) values for test fuels depend on engine speed. The BSFC values obtained from SB20 increased by an average of about 13% compare to cED. However, although the lower heating value (LHV) of biodiesel was lower than that of cED, BSFC values of SB3 fuel were lower than that of cED fuel at engine speeds obtained from maximum engine torque and power. The cause of this can be explained by the better combustion, especially at zones of rich-mixture, owing to the oxygen content of the biodiesel. Furthermore, when cED fuel was mixed at a rate of 3% with biodiesel which has high viscosity and density values, values of blended fuel also increased, and this caused pump losses to decline. Ong *et al.* [11], Ozener *et al.* [12], Chang *et al.* [13], and Fang *et al.* [14] also presented similar results. The BSFC values decreased the with addition of bioethanol compared to both cED and binary blends (biodiesel-diesel mixing) as a result of it having a lower LHV. When the bioethanol rate was increased in the blend fuels, the BSFC

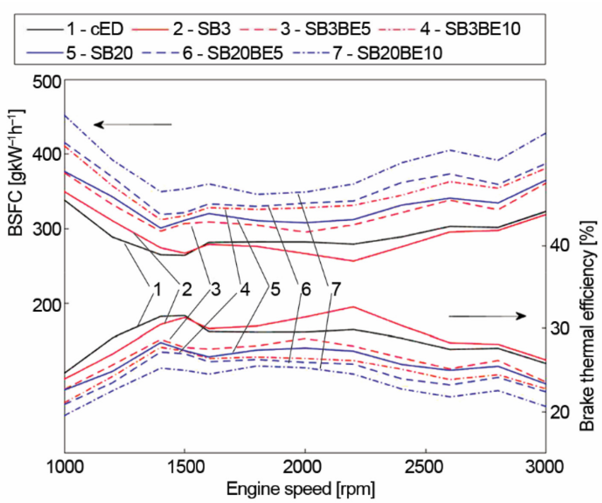

Figure 2. The specific BSFC and BTE results

values also increased. These increased by up to 30.6% compared to cED when using of bio-ethanol. Fang *et al.* [14], Park *et al.* [15], How *et al.* [16] and Lei *et al.* [17] also presented similar results.

Figure 3 presents the volumetric efficiency and exhaust gas temperature of fuels during engine tests. Volumetric efficiency values of SB3 fuel were higher by an average of about 1.12% than those of cED due to the oxygen content, although SB20 had lower values which were an average of approximately 3.7% lower compared to cED. The cause of the lower volumetric efficiency of SB20 is likely to be the increased temperature of the air entering into the cylinder due to the increase in the in-cylinder gas temperature with the higher temperature of the combustion of the bio-diesel. However, the addition of bio-ethanol to binary blends increased the volumetric efficiency values owing to higher latent heat of evaporation of bioethanol.

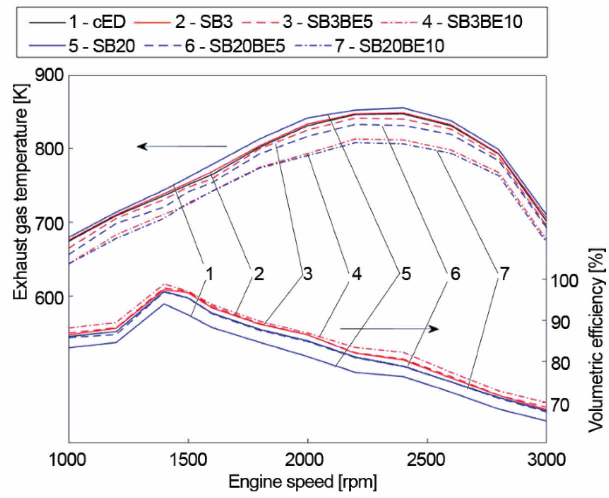

Figure 3. The volumetric efficiency and EGT results

The exhaust gas temperature (EGT) is an important parameter for the explaining emissions. Biodiesel increased the EGT values, and when the bioethanol rate was increased in the blend fuels, the EGT values increased too. The EGT values obtained from B3 and B20 fuels were higher than cED by on average 0.02% and 1.07%, respectively. There was a decrease of about 5% on average with the addition of bioethanol compared to cED fuel. The EGT values were increased by improving the combustion of oxygen in biodiesel. The lower temperature of the combustion of bioethanol caused a decrease of their EGT values. Besides, bio-ethanol absorbs heat from the environment due to its heat of vaporization is low. Therefore, the use of bioethanol decreased EGT values. These results are compatible with studies of Ong *et al.* [11], Rakopoulos *et al.* [18] and Ilkilic *et al.* [19].

Combustion characteristics

In-cylinder pressure and heat release rate resulting at engine speeds (1400 rpm and 2800 rpm) obtained at maximum torque and power are shown in fig. 4. According to the figure, CA obtained at maximum in-cylinder pressure (MICP) has moved away from TDC with the increase of engine speed as the combustion rate (CR) was not increased enough, although the piston speed increased. The MICP values decreased during the increased in engine speed due to the lack of sufficient time for complete combustion. The CA obtained at MICP is related to the SoC and fuel properties. The major parameter for determining the SoC of fuels injected at equal CA is CN. The MICP values measured for each test fuel at both 1400 rpm and 2800 rpm were obtained at a pretty close CA because the CN of cED and SB fuels are very close together as seen in tab. 1.

Start of injection (SoI), SoC, combustion period (CP), and ignition delay (ID) are the foremost parameters for analysis of combustion characteristics. In compression ignition engines, fuel injected in cylinder does not combustion immediately due to the temperatures of the fuel and the compressed air are not equal to each other. The instant at which the fuel starts burning is called SoC. The ID is the duration between SoI and SoC. The period between SoC and end of combustion is CP which is also an indicator for CR. Table 5 shows change depending on CA and the time of CP and ID values for all test fuels at 1400 rpm and 2800 rpm.

Table 5. The ID and CP of test fuels

	SoI	SoC	ID	CP	SoI	SoC	ID	CP
Fuels	bTDC [°CA]		Throughout CA [ms]		bTDC [°CA]		Throughout CA [ms]	
	1400 rpm				2800 rpm			
cED	329	347	2.2394	6.1964	331	350	1.1404	2.3866
SB3	329	347	2.2323	6.0777	332	350	1.1389	2.3037
SB3BE5	328	348	2.4744	5.9283	332	351	1.2538	2.1825
SB3BE10	328	348	2.5968	5.8416	331	352	1.3301	2.0828
SB20	329	347	2.2302	5.9648	331	350	1.1381	2.2485
SB20BE5	329	348	2.3863	5.5575	331	352	1.2582	1.9667
SB20BE10	328	348	2.4932	5.4376	332	352	1.3036	1.8855

The MICP was increased by using biodiesel. This can be explained in that the oxygen in the biodiesel momentarily increased the CR. However, a slight decrease in ID time of binary fuels led to increased MICP values. But when the biodiesel rate increased in the blend fuels, the MICP also decreased due to the worse injection characteristics owing to the high values of viscosity and density and decreased combustion efficiency. Ozsezen [20], Sahoo and Das [21], Dhar *et al.* [22], Rounce *et al.* [23], Su *et al.* [24], and Lesnik *et al.* [25] have revealed similar results. The addition of bioethanol to blend fuels increased MICP values by its high CR. The ID of ternary fuels increased by bioethanol decreases the CN of blends. This caused more fuel stack to be former at the point of SoC, and thus the MICP of ternary fuels increased due to an increasing amount of fuel started to burn suddenly at the end of ID. These results are very similar to those obtained from the studies of Xing-Cai *et al.* [26], Rakopoulos *et al.* [18], Lapuerta *et al.* [27], and Anbarasu *et al.* [28].

According to heat release rate results, the maximum heat release rate (MHRR) increased with rising of engine speed due to the worse injection characteristics of biodiesel, but this improved somewhat at high engine speed. As seen in fig. 4, MHRR values obtained from both SB3 and SB20 were higher than that of cED, and when the biodiesel rate increased in the blend fuels, the MHRR also increased at 1400 rpm. Although MHRR values of SB3 and SB20 fuels were higher than cED, the MHRR value of B20 was lower than that of B3 at 2800 rpm. The BE added into SB3 and SB20 fuels increased MHRR values at 1400 rpm, but it decreased MHRR values except for those from SB20BE10 fuel. Su *et al.* [24], Xing-Cai *et al.* [26], Rakopoulos *et al.* [18], Lapuerta *et al.* [27], Anbarasu *et al.* [28], Chen *et al.* [29], Qi *et al.* [30], Zhu *et al.* [31], and Imtenana *et al.* [32] also presented similar results in their studies.

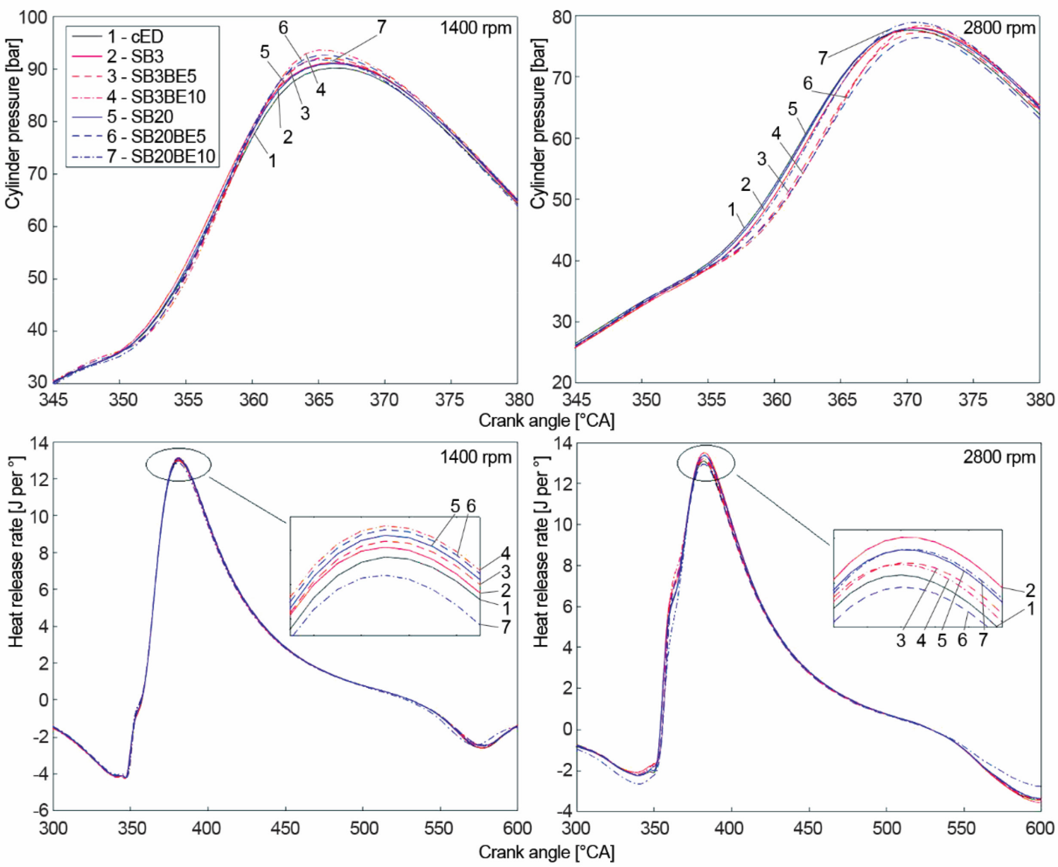

Figure 4. Cylinder pressure and heat release rate variation 1400 rpm and 2800 rpm

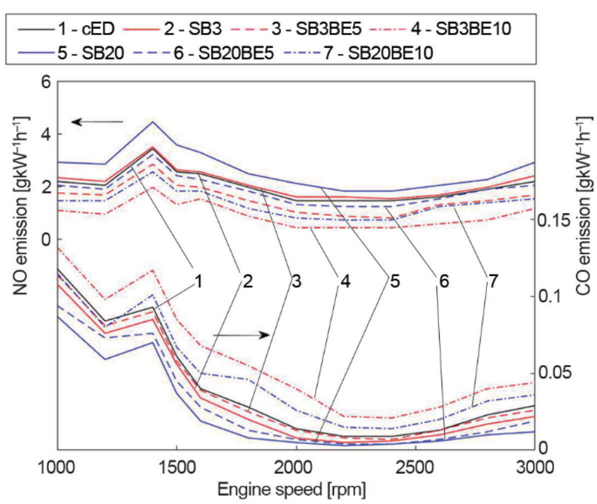

Figure 5. The variation in CO and NO emissions at different engine speed

Exhaust emissions

Exhaust gas emissions were measured as CO [% vol], HC [ppm], NO [ppm], and smoke opacity. These emission values were converted to the units of [$gkW^{-1}h^{-1}$] as the study of Pilusa *et al.* [33].

The major reason for the formation of CO emissions in internal combustion engines is the deficiency of the amount of oxygen in combustion chamber, as given in the literature [34, 35]. Figure 5 shows that while biodiesel decreased CO emission values, bioethanol increased them. Less air is needed during combustion as the stoichiometric air-fuel rate of biodiesel is lower than that of cED. The CO emissions of B3 and B20 fuels decreased by an average of 22.7% and 50%, respectively, compared to cED. The CO emission values of bioethanol blends increased by an average of about 80% depending on a longer ID and CN was decreased with the addition of bioethanol to binary fuels. Lei *et al.* [17], Fattah *et al.* [36], Lesnik *et al.* [25], and Mofijur *et al.* [7] also presented similar results.

The air entering into cylinder contains approximately 78% nitrogen. Unreacted nitrogen and oxygen atoms normally lead to the formation of different nitrous oxide compounds, NO_x, at very high temperatures. After these NO_x are released into atmosphere, they lead to acid rain. Figure 5 presents the NO emissions of binary and ternary blends. The NO emission values when using biodiesel increased due not only to the oxygen content of biodiesel but also its higher EGT values. While there was an average rise of 5.7% of NO emission values obtained with B3 fuel, values from B20 were higher by an average of 31.3% than those of cED. The addition of bioethanol to binary fuels decreased NO emissions by an average of about 55%, as the temperature of combustion was decreased due to a higher latent heat of evaporation of bioethanol. Yilmaz *et al.* [3], Dhar *et al.* [22], Jagadish *et al.* [37], Yılmaz [38], and many researchers have demonstrated similar results in literature.

Emissions of HC occur due to incomplete combustion, decreasing of combustion temperature and lack of oxygen. In particular, the extinction of the flame between cylinder wall and piston causes HC emissions [34, 35]. The variations in the HC emission of test fuels are presented in fig. 6. The HC emissions of B3 and B20 fuels were lower by an average 9.5% and 39.25%, respectively, than those of cED fuel. Oxygen in biodiesel improved combustion efficiency and thus it increased the EGT. These results were compatible with the studies of Mofijur *et al.* [7], Rounce *et al.* [23], Lesnik *et al.* [25], Fattah *et al.* [36], and Parekh *et al.* [39] in the literature. The flame of ternary fuels was burned out before it reached the cylinder wall as the CR of bioethanol is higher. Therefore, the HC emission values obtained with using bioethanol increased by an average of 1.5 fold compared to cED. These were similar results to those of Xing-Cai *et al.* [26], Jagadish *et al.* [37], and Shi *et al.* [40].

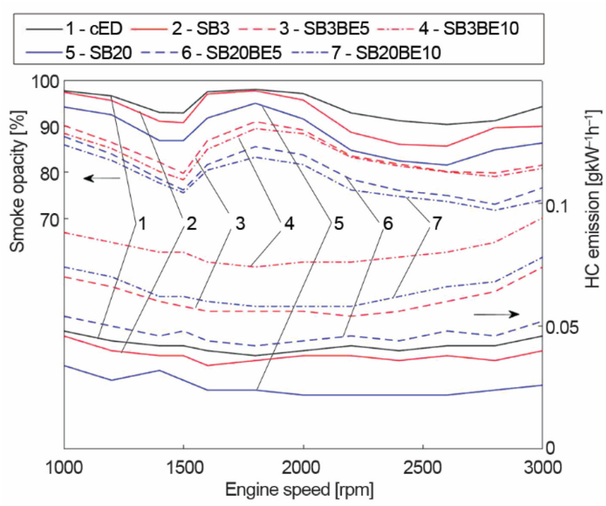

Figure 6. The variation in smoke opacity and HC emissions at different engine speed

Deficient oxygen causes solid carbon particles to form at the zone of intensive HC fuel during combustion. As seen in fig. 6, smoke opacity values decreased due the oxygen content of both biodiesel and bioethanol. The sufficient amount oxygen for carbon atoms was provided with oxygen in the blend fuels, and thus the smoke opacity values were decreased for carbon atoms release from the exhaust as forms of CO or CO_2. The smoke opacity values were decreased by an average of about 6.5% and 17%, respectively, when using biodiesel and bioethanol compared to cED fuel. This result were compatible with studies of Lapuerta *et al.*

[27], Qi *et al.* [30], Kegl [41], Lin and Li [42], Nabi *et al.* [43], Enweremadu *et al.* [44], Prasad *et al.* [45], , Kim and Choi [46], Rakopoulos *et al.* [47], and Shi *et al.* [40].

Conclusions

The results obtained using blends of cED, biodiesel and bioethanol are as follows.

- Both bioethanol and biodiesel mixed with cED fuel increased BSFC values due to the fact that their LHV are lower than those of cED fuel. But SB3 fuel decreased BSCF due to its oxygen content and with decreasing pump losses.
- The volumetric efficiency values were decreased using biodiesel due to it having EGT values which are higher than cED. However, bioethanol increased volumetric efficiency as it has a higher latent heat of evaporation.
- The combustion characteristics showed that use of biodiesel and bioethanol usually increased MICP and MHRR values. It could be expected that the engine performance of binary and ternary fuels is better than that of cED as their MICP and MHRR values are higher. But oxygen in biodiesel and bioethanol increases CR, and it shortens the CP. Therefore, the flame formed during the CP is burned out without expanding, so the flame diameter is smaller. This causes the pressure force formed at burn end to have a smaller piston surface.
- The effect on ID of biodiesel was negligible as the CN of the biodiesel produced was almost equal to cED. Nevertheless bioethanol decreased the CN and thus it increased to ID. Both biodiesel and bioethanol decreased CP owing to their oxygen contents oxygen, and this caused an increase in the CR.
- Although biodiesel decreased CO, HC, and smoke opacity emissions due to its oxygen content, it increased NO emission values owing to high EGT. Bioethanol decreased NO emission values because of its low EGT and decreased smoke opacity with cleaner burning as it has a lower number of carbon atoms. However, it increased HC and CO emissions as it has higher latent heat of evaporation and high CR.

These results show that ternary fuels could be used easily without any modification in diesel engines because, in general, they improved exhaust emissions and show similar fuel properties and combustion characteristics, although they did adversely affect engine performance.

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