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Effects of Biodiesel Fuels Produced from Vegetable Oil and Waste Animal Fat on the Characteristics of a TDI Diesel Engine

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ABSTRACT

In this study, four different biodiesel fuels obtained from corn oil, safflower-rapeseed oil mixture (50%-50% v/v), waste chicken fat, and waste fleshing oil were tested in a six-cylinder, water-cooled, TDI diesel engine. Vegetable oil and waste animal fat origin biodiesel fuels' effects on the performance, injection, combustion and emission characteristics of test engine were compared with each other and petroleum-based diesel fuel as reference fuel. Biodiesel fuels (regardless of their feedstock) increased in-cylinder gas pressure, brake specific fuel consumption, and NO_x emissions while decreased THC and CO emissions compared to pure diesel fuel. In comparison to petro-diesel, the start of fuel injection timing advanced but the end of fuel injection timing retarded with biodiesels. In addition, comparatively higher fuel injection pressure values were attained with all biodiesel fuels. Waste animal fat and vegetable oil origin biodiesel fuels showed similar in-cylinder gas pressures, fuel injection characteristics and brake specific fuel consumption values. However, vegetable oil-based biodiesel fuels' CO emissions were lower than those of waste animal fat-based biodiesels, but NO_x emissions were higher.

1. INTRODUCTION

The share of pollutants from the transportation sector in the total environmental pollution has been increasing. In order to decrease tailpipe emissions, very strict emission regulations are being come into force and the upper limits are reduced step by step towards the ultimate target of near-zero emissions. In every new emission standard, meeting the permitted exhaust emission limits (especially in diesel engines) becomes more challenging for the automotive industry. One of the methods that can be considered to reduce exhaust emissions released from vehicles (together with the improvements in fuel injection systems and strategies, combustion chamber design, and exhaust gas after-treatment technologies) is the usage of environmentally friendly alternative energy sources in internal combustion engines.

Biodiesel is a renewable, biodegradable, domestically producible, and environmentally friendly alternative diesel fuel. It can be produced from various feedstocks such as vegetable oils, animal fats and their wastes [1]. Diesel engines can be powered with neat biodiesel fuel. According to the European Union diesel fuel standard (EN-590), diesel fuel can contain up to 7% (on volume basis, v/v) biodiesel which meets the specifications in the European biodiesel fuel standard (EN-14214), regardless of its feedstock. Although there are many feedstocks that can be used in biodiesel production, the vast majority of industrial-scale biodiesel comes from high-quality edible vegetable oils. The use of high-quality but unacceptably expensive edible oils in the biodiesel industry inevitably increases its unit price as well as negatively affects the food chain by increasing the prices of those vegetable oils. Low-cost feedstocks such as waste frying oils and waste animal fats should be preferred in biodiesel production in order to make it an economically viable fuel and to prevent the rise in edible oil prices [2]. In addition to its positive impact on biodiesel fuel's break-even price, the usage of waste feedstocks will prevent the environmental contamination caused by their disposal.

It should be strongly highlighted that various triglycerides as the biodiesel feedstock (vegetable oils, animal fats or their wastes) will have different fatty acid compositions, leading to different physico-chemical properties [3]. Biodiesel fuels having different fuel properties inevitably influence the engine characteristics. Because of this, the effects of biodiesel fuels of different origin on the diesel engine characteristics should be investigated in detail. However, when the studies in the literature about the effects of biodiesel fuels on engine characteristics are examined, it is seen that these studies are generally carried out with vegetable oil-based biodiesels. In particular, the number of experimental articles comparing the influences of biodiesel fuels of vegetable oil and animal fat origin under the same engine operating conditions is quite limited.

Barrios et al. [4] produced biodiesel fuels from soybean oil and animal fat. Animal fat feedstock was a blend of pork, poultry and beef fat. They prepared six different biodiesel-diesel fuel blends (10-20-25-30-40-50 %, v/v). Biodiesel fuels were not used in the engine tests as neat fuel. The authors have detected higher brake specific fuel consumption (BSFC) values and brake thermal efficiencies (BTE) with all biodiesel fuels compared to petro-diesel fuel (PDF). All biodiesel blends decreased particulate matter (PM) emission but caused to higher oxides of nitrogen (NO_x) emissions than diesel fuel. Although there were no significant differences between NO_x emissions of biodiesel fuels of different origin, PM emissions of animal-fat based biodiesel blends were less than those of vegetable oil-based biodiesel blends. Animal fat-based biodiesel fuel blends had better engine characteristics than soybean oil-based biodiesel blends especially at 40% and 50% biodiesel-diesel fuel concentrations. In order to minimize harmful emissions, BSFC and maximize BTE, the authors have concluded that 30% animal fat based biodiesel-diesel fuel was the ideal blend ratio.

Ahmed et al. [5] investigated the effects of beef tallow-based biodiesel fuel and its blends with PDF in the ratios of 20-40-60% (v/v). Engine tests were conducted in a single cylinder, four-stroke, water-cooled diesel engine. BSFC values of all test fuels decreased with increasing engine load. Biodiesel fuels' BSFC values were higher than that of PDF at all loads and this difference increased as biodiesel percentage of the blend increased. BTE of all test fuels increased as the engine load was increased. Biodiesel fuels had relatively higher BTE at all operating conditions. The authors detected that biodiesel fuel and its blends started to burn earlier than PDF. Although the max in-cylinder pressures were very close to each other, the crank angles at which the max in-cylinder pressures were attained advanced with biodiesel fuels. Biodiesel fuel and its blends reduced carbon monoxide (CO), total hydrocarbon (THC) and smoke emissions but increased NO_x emissions. In order to decrease NO_x emissions of biodiesel fuels, the authors used exhaust gas recirculation (EGR) in the ratios of 10-20-30%. At the EGR ratio of 10%, lower bsfc, higher BTE, lower CO and THC emissions were observed. In addition, the decrease in NO_x and smoke emission was 16.5% and 17.5%, respectively. The authors reported that animal fat origin biodiesel-diesel fuel blend ratio of 20% could be used in a diesel engine with 10% EGR application without causing higher NO_x emissions and bsfc values.

Sathiyagnanam et al. [6] produced biodiesel fuel from waste pork lard. They blended biodiesel fuel with PDF in the ratios of 25-50-75% (v/v). Engine test were carried out in a one-cylinder, four-stroke, water-cooled, DI diesel engine. Throughout the engine tests, engine speed was not changed (1500 rpm) while engine load was increased from 0% to full load with the steps of 25%. Biodiesel fuel and its blends had higher bsfc and lower BTE values than diesel fuel at all engine loads tested. The combustion started comparatively earlier for biodiesel fuels than diesel fuel. Peak in-cylinder pressure values declined with increasing biodiesel content in the blend. The relatively shorter ignition delay periods for biodiesel fuel and its blends were reported. Because of the longer ignition delay and better volatility, the premixed combustion phase of PDF was more intense than biodiesel and its blends. Biodiesel fuels significantly decreased CO, HC and smoke emissions. Nevertheless, their NO_x emissions were higher. To reduce NO_x emissions and to determine the optimum ratio, the various percentages of urea were injected to the engine exhaust. The authors expressed that 30% urea and 70% water gave the max NO_x reduction without deteriorating CO emissions.

In this experimental study, in order to partially fill the gap in the literature about the impacts of biodiesel fuels of different origin on the engine characteristics, the influences of biodiesel fuels obtained from two different waste animal fats and two different vegetable oils on the performance, injection, combustion and emission characteristics of a TDI diesel engine were investigated and compared with petroleum-based diesel as reference fuel.

2. MATERIALS AND METHODS

Corn oil biodiesel (COB) and safflower-rapeseed oil biodiesel (SRB) fuels as the vegetable oil-based biodiesels, waste fleshing oil biodiesel (WFB) and waste chicken fat biodiesel (WCB) fuels as the animal fat-based biodiesels were used in the engine tests. Waste fleshing oil was obtained from the solid waste processing plant in Istanbul Leather Organized Industrial Zone while waste chicken fat was obtained from the rendering facility at Beypilic Bolu Factory. Corn oil and PDF were purchased from local store and gas station. Biodiesel productions from corn oil, waste chicken fat and waste fleshing oil were performed in the pilot-scale biodiesel plant at Kocaeli University. SRB fuel was obtained from DB Agricultural Energy Co. Inc. in Izmir. Physico-chemical fuel properties of test fuels were given in Table 1.

Engine tests were carried out in a four-stroke, six cylinders, direct-injection, turbocharged diesel engine. Technical specifications of the test engine were shown in Table 2. A schematically view of the test system was depicted in Fig. 1. The engine was tested at the condition of 1400 rpm and 600 Nm engine load. No modifications were made to the engine prior to the engine tests. The test engine was equipped with an in-line type fuel injection pump. In-cylinder pressure was measured via Kistler (6061B) pressure sensor while Kistler (6005) sensor was used for fuel-line pressure. AVL SESAM FITR exhaust emission analyzer measured the exhaust emissions. Specifications of the exhaust emission device were given in Table 3.

TABLE I
TEST FUELS' PHYSICO-CHEMICAL FUEL PROPERTIES

Property	Unit	PDF	SRB	COB	WCB	WFB
Density (15 ºC)	$kg.m^{-3}$	829	883.6	886.0	889.7	876.7
Viscosity (40 ºC)	$mm^2.s^{-1}$	2.96	4.3	4.6	5.3	4.7
Flash Point	ºC	63	186	169	169	168
Water Content	ppm	20	240	440	440	410
Acid Value	$mgKOH.g^{-1}$	-	0.28	0.21	0.43	0.28
Monoglyceride	% (w/w)	-	0.49	0.06	0.02	0.06
Diglyceride	% (w/w)	-	0.15	0.17	0.05	0.02
Triglyceride	% (w/w)	-	0.01	0.06	0.06	0.20
Free Glycerol	% (w/w)	-	0.001	0.01	0.008	0.01
Total Glycerol	% (w/w)	-	0.15	0.06	0.03	0.05
Copper Strip Corrosion (3 h, 50 ºC)	Degree of corrosivity	No 1	No 1	No 1	No 1	No 1
Heating Value	$MJ.kg^{-1}$	45.96	40.05	39.88	39.69	39.89
Cetane Number	-	56.8	53.0	54.2	52.3	58.8
Methanol Content	% (w/w)	-	0.00	0.03	0.05	0.01
CFPP	ºC	-15	-9	-5	3	10

TABLE II
TECHNICAL SPECIFICATIONS OF THE TEST ENGINE

Engine	6 liter, Ford Cargo
Type	Direct Injection, turbocharged-intercooled, four-stroke, water cooled
Number of cylinder	6
Bore - stroke	104.00 – 114.9
Compression ratio	16.4:1
Injection pump	In-line type
Injector opening pressure	197 bar
Maximum power	136 kW (2400 rpm)
Maximum brake torque	650 Nm (1400 rpm)

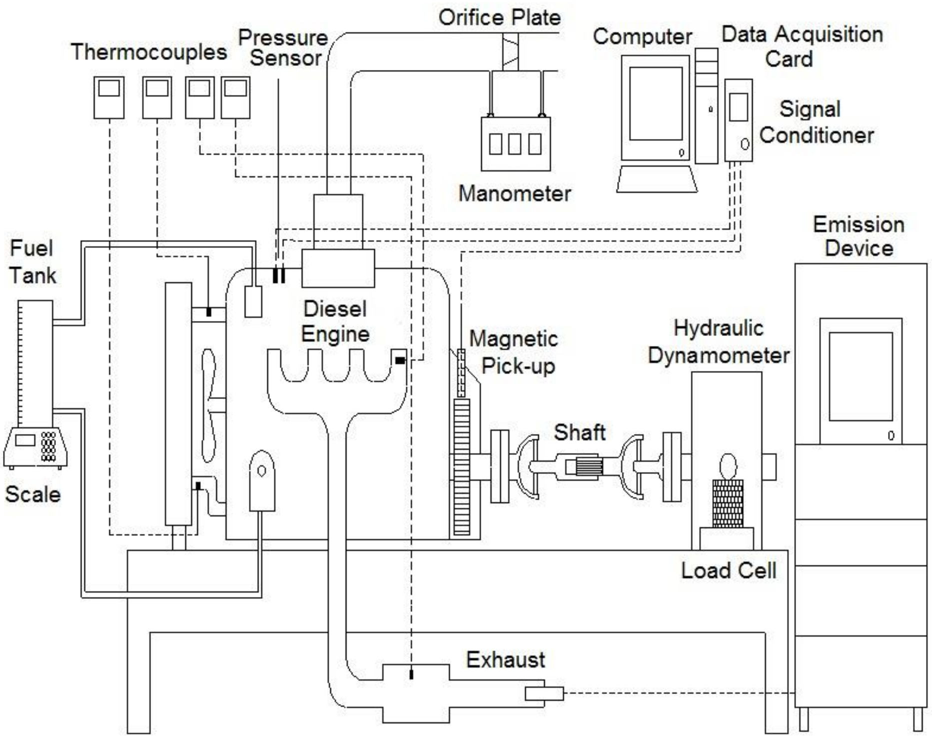

Figure 1. The experimental setup.

TABLE III
SPECIFICATIONS OF EXHAUST EMISSION DEVICE

Parameter	Unit	Measuring Range	Accuracy
HC	ppm	0-20,000	Better than 2% ± of measured value
CO	ppm	0-8,000 (low) 8,000-100,000 (high)	Better than 2% ± of measured value
NO_x	ppm	0-10,000	Better than 2% ± of measured value

3. RESULTS AND DISCUSSION

3.1. Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) is one of the most critical parameters used for comparing the effects of different fuels on engine performance. Fig. 2 shows the BSFC values of the test fuels. As can be understood from the figure, all biodiesel fuels led to increment in BSFC values. Comparative to BSFC value of PDF, the rise in BSFC values was 11.8%, 13.7%, 11.8% and 10.8% for WFB, WCB, COB and SRB, respectively. The high BSFC values of biodiesel fuels can be explained with their comparatively low calorific values than that of PDF. As given in Table 1, the calorific values of biodiesel fuels used in engine tests were about 13% lower than that of PDF. Buyukkaya [7] found similar results in their studies.

Among the biodiesel fuels, WCB had the highest BSFC value. The relatively high viscosity and density values of WCB may have negatively affected the atomization quality and inevitably the combustion efficiency, resulting in higher BSFC value. SRB had lower BSFC value than the other biodiesel fuels. This may be resulted from its low viscosity and high calorific value. WFB and COB fuels had were very close BSFC values. It is quite remarkable that viscosity and calorific values of these biodiesel fuels were also almost the same (Table 1).

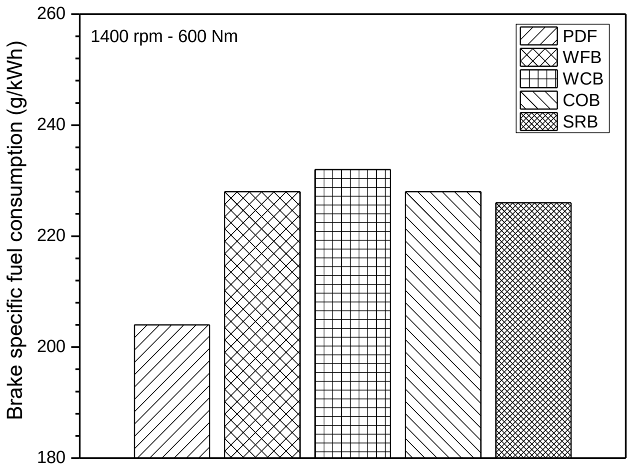

Figure 2. Brake specific fuel consumption of test fuels.

3.2. Fuel Injection and Combustion Characteristics

Injection characteristics such as start and end of injection, injection duration and injection pressure directly affect the combustion phenomenon and inevitably exhaust emission profile of the engine [8]. Therefore, it is very important to analyze the injection characteristics of different fuels. Test engine is equipped with mechanically controlled in-line type fuel injection system. Before presenting and interpreting the data on the fuel injection characteristics of test fuels, it will be helpful to remember some critical issues on this type of fuel injection system. In mechanic fuel injection systems, fuel injection is performed with the fuel pressure. Namely, high-pressure transfer pump compress the fuel and this rise in pressure progresses in fuel line and reaches injector. When the injector pressure exceeds the spring pressure that presses the injector needle down, the injector needle lifts and fuel injection begins. In-line type fuel injection system controls the end of injection process. In order to increase the fuel quantity to the engine, it regulates the injector closing timing. In other words, if it is necessary to inject more fuel, the end of injection is delayed [9].

Since the injector needle-lifting sensor was not used in this study, the injector opening pressure (197 bar) was accepted as the start of injection. Fuel line pressure values obtained with test fuels were given in Fig. 3. As can be seen in the figure, start of injection advanced with all biodiesel fuels compared to PDF. SRB and WCB fuels had almost the same start of injection timing while WFB and COB fuels were in the second and the third order, respectively. The earlier start of injection with biodiesel fuels relative to PDF can be explained with their compressibility. If a fuel is less compressible, fuel line pressure will increase faster and thus injection will start sooner [10]. Because of this, the fuel type that is used in a diesel engine with mechanical fuel injection system directly influences the start of injection and the other injection characteristics. Two critical properties affecting the injection timing are the propagation speed of the pressure waves in fuel line (speed of sound) and the capacity of the fuel to dampen this pressure (bulk modulus) [11]. Related studies have revealed that when biodiesel fuels are used, in comparison to PDF, pressure waves proceed faster and the fuel dampens the pressure less [12]. As a combined result of these two factors, fuel line pressure increases faster with biodiesel fuel and so the start of injection advances.

The end of fuel injection retarded for all biodiesel fuels. Since more fuel needs to be injected into the engine in case of biodiesel usage (see Fig.2), the in-line type fuel injection pump retarded the injector closing by regulating the end of injection, as mentioned above. With all biodiesels (regardless of the feedstock), the injection duration was prolonged because of the advanced start and the delayed end of fuel injection. Another important point is the injection pressures of all biodiesel fuels, which were higher than those of PDF.

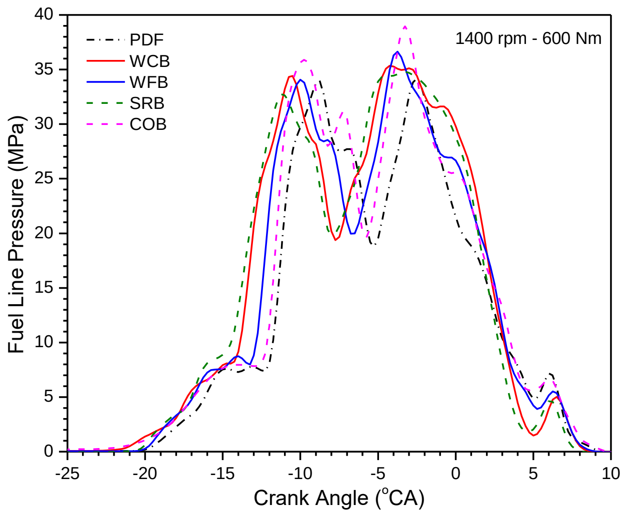

Figure 3. Fuel line pressures of test fuels.

In-cylinder pressure and heat release rate (HRR) values and their alterations with crank angle give critical information about the start, the propagation, and the end of combustion phenomenon. These data have critical importance in order to compare the combustion characteristics of alternative fuels with different physico-chemical fuel properties. In-cylinder pressures and HRRs of test fuels were depicted in Fig. 4. As seen, slightly higher in-cylinder pressures were attained with biodiesel fuels both vegetable oil and animal fat origin compared to PDF. Two main reasons for the higher in-cylinder pressures are biodiesels' the earlier start of injection timings and their oxygen contents. The extra oxygen in the combustion media coming from the biodiesel chemical structure increases the flame speed, resulting in higher in-cylinder pressures [13].

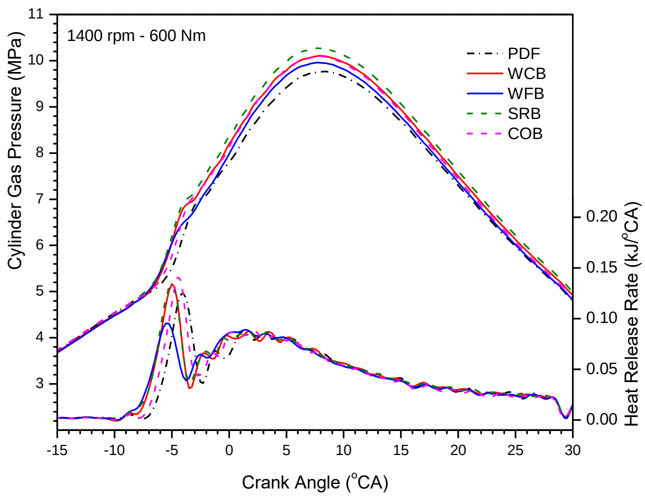

Figure 4. Cylinder gas pressure and heat release rates of test fuels

As given in Fig. 5, the maximum in-cylinder gas pressure (P_{max}) values of vegetable oil and animal fat-based biodiesel fuels were close to each other. Among the test fuels, the highest in-cylinder pressure of 10.27 MPa was attained with SRB fuel. The maximum gas pressures obtained with WCB and COB were almost the same. Similar results can be found in the literature [14]. When the HRR graphs were viewed it is seen that start of combustion timings of all biodiesel fuels were earlier compared with PDF and also relatively higher HRR values were attained with biodiesels.

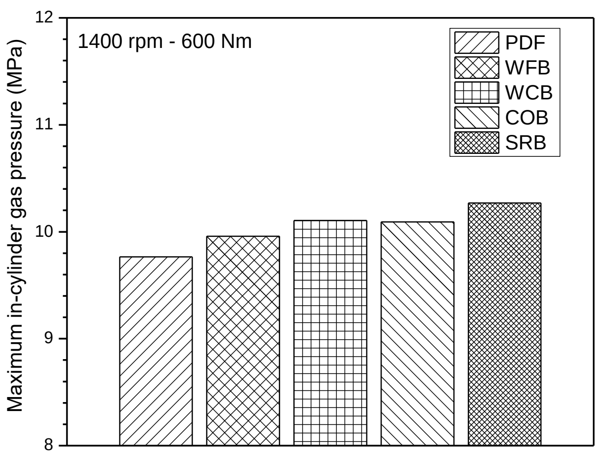

Figure 5. P_{max} values of test fuels

Test fuels' some critical fuel injection and combustion data that were obtained by analyzing the fuel-line pressures and HRR graphs can be seen in Table 4. When the results are examined, it is seen that the start of fuel injection timing of the test fuels was different from each other. The difference in the fuel properties of the test fuels caused the different fuel injection characteristics. The start of fuel injection of PDF retarded as compared to biodiesel fuels and the biggest difference of 2 crank angle (ºCA) was detected with SRB fuel. In the experimental study that was performed at full load, Monyem et al. [15] reported approximately 2 ºCA advanced start of fuel injection with biodiesel fuels relative to PDF. As can be understood from the Table, all biodiesel fuels started to burn at earlier crank angles than PDF. Cetane number is a critical indicator of self-ignitability of a fuel. According to the European diesel fuel standard (EN-590), the minimum cetane number has to be 51. Nevertheless, cetane number of LSD and ULSD fuel (euro-diesel) is higher than 55. Cetane number of PDF used in engine tests was 56.8. Except for WFB, PDF's cetane number was higher than those of biodiesel fuels (see Table 1). The comparatively higher saturated fatty acid content of WFO than the other biodiesels is the most important parameter increasing cetane number of this biodiesel fuels. The highest cold filter plugging point value (10 ºC) of WFB among the test fuels is another indicator of its high saturation level. Although cetane number of WFB was higher, its start of combustion was relatively later than SRB fuel. Despite SRB's less cetane number, it's the earlier start of injection and better volatility resulted in the earlier start of combustion.

Ignition delay (ID) can be defined as the time interval between the start of injection and the start of combustion [16]. The maximum difference among ID periods of the test fuels was measured between PDF and WCB. Although the start of combustion of WCB was earlier, its start of injection was about 2 ºCA earlier than PDF, leading to a longer ID period. The minimum ID value was detected for WFB, which had the maximum cetane number.

TABLE IV
FUEL INJECTION and COMBUSTION RESULTS

Parameter (ºCA)	PDF	SRB	COB	WCB	WFB
Start of Combustion (b TDC)	7.75	9.75	8.00	8.50	9.25
Start of Injection (b TDC)	11.25	13.25	11.50	13.00	12.25
Ignition Delay	3.50	3.50	3.50	4.50	3.00

3.3. Exhaust Emission Characteristics

Carbon monoxide (CO) is a colorless, odorless and highly toxic gas. When there is not enough oxygen in the combustion reaction in order to convert the carbon atoms into carbon dioxide, CO emission forms [17]. The most important parameter influencing CO emission is the fuel/air equivalence ratio. The importance of the other parameters that should be considered in terms of CO emission such as injection advance, the shape of the combustion chamber, etc. is less than that of the fuel/air equivalence ratio. Especially fuel-rich mixtures cause to increment in CO emission [18]. CO emission profiles of test fuels were given in Fig. 6. As can be seen, CO emission of PDF was higher than those of biodiesel fuels. The most critical parameter on the less CO emissions of biodiesel fuels is their oxygen contents. Biodiesel fuels have about 10% oxygen in their chemical structures. This extra oxygen coming from the fuel in the combustion media improves the combustion reaction, resulting in less CO emission. In addition, the advanced start of fuel injection timing and the higher fuel injection pressure that are attained with biodiesel fuels (see Fig. 3) are also effective on their better CO emissions. Canakci and Gerpen [19] reported similar results with biodiesel fuels. When biodiesels are compared to each other, it is seen that CO emissions of vegetable oil-based biodiesel fuels were significantly less than those of animal fat-based biodiesels. WFB and WCB fuels' relatively higher viscosity and density values worsening the atomization quality may be influential on their high CO emissions.

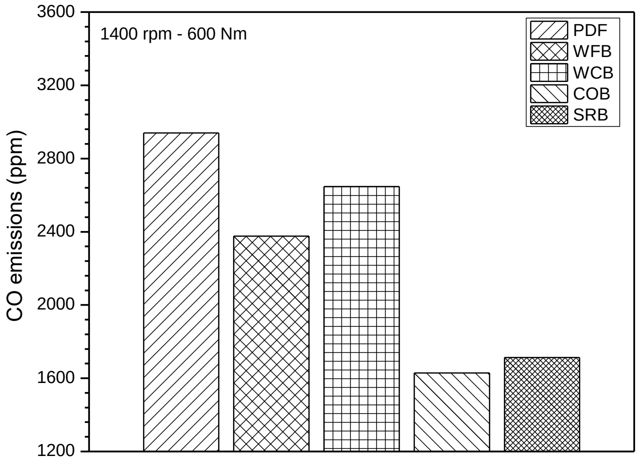

Figure 6. CO emission values of test fuels

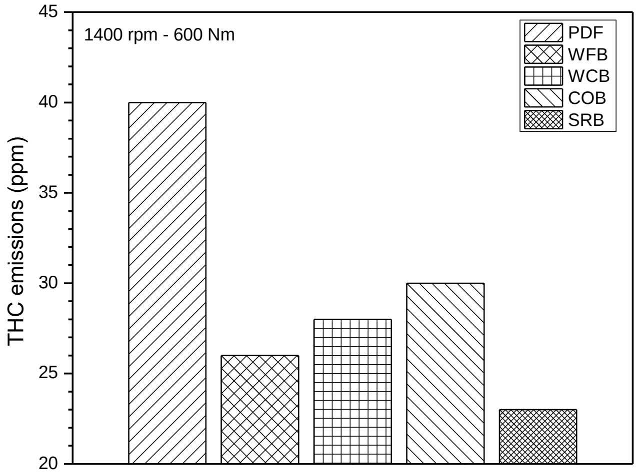

Figure 7. THC emission values of test fuels

Hydrocarbon emissions (HC) are the result of incomplete combustion and indicate unburned or partially burned fuel in the exhaust emission. Although HC emissions are incomplete combustion products like CO emissions, the parameters such as the chemical structure of the fuel, combustion chamber geometry (length of flame paths) and engine operating conditions are more critical for this emission type compared to air excess ratio. HC emissions from engines are generally divided into two different groups: Total Hydrocarbon (THC) emissions and non-methane Hydrocarbon emissions (NMHC) [20]. THC emissions of all test fuels were depicted in Fig. 7. THC emissions of biodiesel fuels were significantly lower than that of PDF. Despite biodiesel fuels' higher kinematic viscosity and density values deteriorating the fuel atomization quality and causing higher and heavier fuel droplets, their relatively lower THC emissions might be explained by the earlier fuel injection timing and the higher fuel injection pressures. In addition, biodiesel fuels' molecular oxygen content can also be considered for their lower THC emissions. Biodiesel fuels' THC emissions were close to each other. Among the biodiesel fuels, COB and SRB had the highest and the lowest THC emissions, respectively. Sanli [21] also detected lower THC emissions with biodiesel fuels compared to PDF.

Nitrogen Oxide (NO_x) emissions can be considered as the most critical one among diesel engine exhaust emissions. NO_x emissions occur with the reaction of oxygen and nitrogen at high temperatures (approximately 1800 K and higher degrees). A large part of NO_x emissions is composed of NO emissions, a small part is NO_2 emissions, and the remaining trace amount is other oxygen-nitrogen combinations. In-cylinder temperatures and pressures, air/fuel ratio, fuel's cetane number, combustion duration, the oxygen concentration in combustion media, fuel injection timing, and fuel injection pressure are the critical parameters in terms of NO_x emissions [22]. As can be seen in Fig. 8, all biodiesel fuels (regardless of its feedstock) caused higher NO_x emissions. As compared to PDF, the increase in NO_x emission was 4.7%, 7.7%, 9.9% and 11.2% for WFB, WCB, SRB and COB, respectively. The higher NO_x emissions of biodiesel fuels may be caused by their higher fuel injection pressures, the advanced start of fuel injection (see Fig.3), the higher in-cylinder pressures and heat release rates (see Fig. 4). In addition, the molecular oxygen contents of biodiesel fuels could also be effective on this result. Chen et al. [23] reported higher NO_x emissions with biodiesel fuels. Another issue that should be underlined in terms of NO_x emissions is that the NO_x emissions of animal fat-based biodiesels were lower than those of vegetable oil-based biodiesels. Both of WFB and WCB had better NO_x emissions than SRB and COB (on average 4% lower). Relatively higher in-cylinder pressure and HRR values of COB and SRB could be reasons for the higher NO_x emissions of these biodiesel fuels (see Fig. 4). Moreover, the higher cetane number of animal-fat based biodiesels could also be effective on their better NO_x emissions results. Wyatt et al. [24] also detected lower NO_x emissions with animal-fat based biodiesel fuels than vegetable oil-based biodiesels.

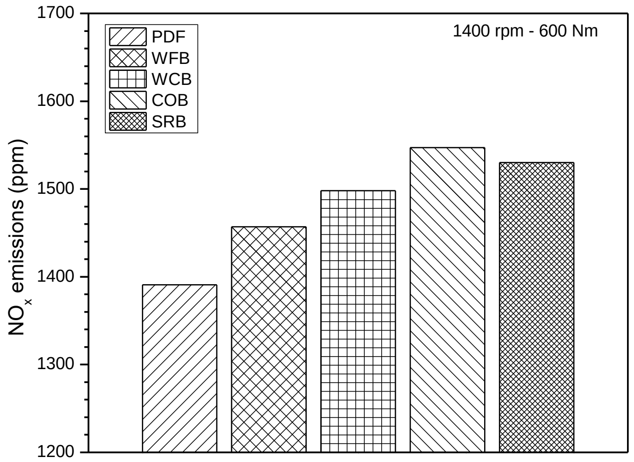

Figure 8. NOx emission values of test fuels

4. CONCLUSIONS

The use of alternative fuels in diesel vehicles is a critical issue in order to reduce harmful emissions released from these vehicles. Biodiesel is one of the important, environmentally friendly and sustainable alternative fuels. Although biodiesel can be produced from many different feedstocks, a very portion of industrial biodiesel production is obtained from vegetable oils. If biodiesel fuel is produced from different feedstocks, the unit price of biodiesel will be affected as well as the engine characteristics will be affected since the fuel properties will change. In this study, it was aimed to compare the effects of vegetable oil-based biodiesels and animal fat-based biodiesels on the performance, combustion, injection and exhaust emission characteristics of a TDI diesel engine. Petroleum-based diesel fuel was used as the reference fuel. Engine tests were conducted at the engine operating conditions of 1400 rpm and 600 Nm. BSFC values of all biodiesel fuels were higher than that of PDF. Animal fat-based and vegetable oil-based biodiesels had close BSFC values. Relatively higher in-cylinder pressures were attained with biodiesel fuels. Although there was no significant difference between them, the highest in-cylinder pressure was measured with SRB biodiesel. Fuel injection pressure was lower with PDF compared to all biodiesel fuels. Compared to PDF, the advanced start of fuel injection and the start of combustion timings were detected with all biodiesel fuels. When the biodiesels were compared each other, it was seen that the start of fuel injection timing of SRB and WCB fuels were almost the same and they was injected approximately 2 ºCA earlier than PDF. Regardless of the feedstock from which it is produced, CO and THC emissions of all biodiesel fuels were lower than PDF, but NO_x emissions were higher. The most significant difference between vegetable oil-based and animal fat- based biodiesels was seen in CO and NO_x emissions. SRB and COB fuels had lower CO emissions

REFERENCES

[1] F. Yasar, "Evaluation of renewable energy source algae as biodiesel feedstock," European Journal of Technique, vol. 9, no. 2, pp. 298-311, 2019.

[2] S. Aydin, "Thorough analysis of combustion and emissions of power generator diesel engine at high idling operations fueled with low percentage of biodiesel blends," European Journal of Technique, vol. 10, no. 1, pp. 184-195, 2020.

[3] S. B. Gok et al., "Fatty acid composition of Silybum Marianum L. seeds and antimicrobial activity of seed oil and silymarin extract," The Journal of Food, vol. 46, no. 1, pp. 110-118, 2021.

[4] C. C. Barrios et al. "Effects of animal fat based biodiesel on a TDI diesel engine performance, combustion characteristics and particulate number and size distribution," Fuel, vol. 117, pp. 618-623, 2014.

[5] S. A. Ahmed, et al., "Evaluation of animal fat based biodiesel blends and effects of exhaust gas recirculation on the suitable blend in single cylinder four stroke diesel engine," Energy Sources Part A: Recovery, Utilization, and Environmental Effects, to be published. DOI: 10.1080/15567036.2020.1862368.

[6] A. P. Sathiyagnanam, et al. "Biodiesel production from waste pork lard and experimental investigation of its use as an alternate fuel in a DI diesel engine," International Journal of Mechanical Engineering and Robotic Research, vol. 1, no. 3, pp. 176-191, 2012.

[7] E. Buyukkaya, "Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics," Fuel, vol. 89, no. 10, pp. 3099-3105, 2010.

[8] W. W. Pulkrabek, "Engineering fundamentals of the internal combustion engine," 1st ed, Pearson Publishing House, USA, 1997.

[9] J. B. Heywood, "Internal combustion engine fundamentals," 1st ed, McGraw Hill, USA, 1989.

[10] P. Richards, "Alternative Fuel Reference Book," 3rd ed, SAE International, USA, 2014.

[11] O. Armas, "Alternative method for bulk modulus estimation of diesel fuels," Fuel, vol. 167, pp. 199-207, 2016.

[12] M. Lapuerta et al., "Bulk modulus of compressibility of diesel/biodiesel/HVO blends," Energy Fuels, vol. 26, no. 2, pp. 1336-1343, 2012.

[13] H. Sanli, "An experimental investigation on the usage of waste frying oil-diesel fuel blends with low viscosity in a common rail DI-diesel engine, Fuel, vol. 222, pp. 434-443, 2018.

[14] E. Alptekin et al., "Combustion and performance evaluation of a common rail DI diesel engine fueled with ethyl and methyl esters," Applied Thermal Engineering, vol. 149, pp. 180-191, 2019.

[15] A. Monyem et al., "The effect of timing and oxidation on emissions from biodiesel-fueled engines," Transactions of the American Society of Agricultural Engineers, vol. 44, no. 1, pp. 35-42, 2001.

[16] P. A. Lakshminarayanan et al., "Ignition delay in a diesel engine, in: Modeling Diesel Combustion," Springer, USA, 2010.

[17] A. A. Abdel-Rahman, "On the emissions from internal combustion engines: a review," International Journal of Energy Research, vol. 22, no. 6, pp. 483-513, 1998.

[18] H. Sanli et al., "Effects of waste frying oil based methyl and ethyl ester biodiesel fuels on the performance, combustion and emission characteristics of a DI diesel engine," Fuel, vol. 159, pp. 179-187, 2015.

[19] M. Canakci, J. Van Gerpen, "Comparison of engine performance and emissions foe petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel," Transactions of the American Society of Agricultural Engineer, vol. 46, no. 4, pp. 937-944, 2003.

[20] M. Wang et al. "Ambient non-methane hydrocarbons (NMHCs) measurement in Boading, China: sources and roles in ozone formation," Atmosphere, vol. 11, no. 11, pp. 1-17, 2020.

[21] H. Sanli, "Influences of biodiesel fuels produced from highly degraded waste animal fats on the injection and emission characteristics of a CRDI diesel engine," International Journal of Automotive Engineering and Technologies, vol. 8, pp. 11-21, 2019.

[22] C. Sayin et al., "Influence of injection timing on the exhaust emissions of a dual-fuel CI engine," Renewable Energy, vol. 33, no. 6, pp. 1314-1323, 2008.

[23] H. Chen et al., "NOx emission of biodiesel compared to diesel: higher or lower?," Applied Thermal Engineering, vol. 137, pp. 584-593, 2018.

[24] W. T. Wyatt et al., "Fuel properties and nitrogen oxide emission levels of biodiesel produced from animal fats," Journal the American Oil Chemists' Society, vol. 82, pp. 585-591, 2005.

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