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Experimental Investigation of Neutralized Waste Cooking Oil Biodiesel/Diesel Mixture and Diesel Fuel in a Diesel Engine at Different Engine Loads

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Abstract

In this study, the effects of neutralized waste cooking oil biodiesel-diesel mixture (B30) and diesel fuels on combustion, performance and emission characteristics were investigated and compared experimentally in a four stroke, single cylinder direct injection diesel engine at different engine loads. For this reason, the test engine was operated with different engine loads including 3.75, 7.5, 11.25, 15 and 18.75 Nm at 2200 rpm engine speed. The variations of in-cylinder pressure, heat release rate, cyclic variations, combustion duration and CO, CO_2, NO_x and soot emissions were investigated. The test results showed that in-cylinder pressure and heat release rate increased with B30 compared to diesel for all engine loads due to better oxidation reactions. CO and soot emissions reduced by about 57.9 % and 25.5 % with biodiesel compared to diesel at 18.75 Nm. It was also found that higher indicated mean effective pressure (imep) was obtained with B30 according to neat diesel. Besides, shorter combustion duration was obtained with B30. Oxidation reactions and performance can be improved with biodiesel compared to diesel. As a result, neutralized waste cooking oil biodiesel-diesel fuel mixture (B30) could be easily used without engine modifications in diesel engines.

Keywords: Biodiesel, Neutralized waste cooking oils, Transesterification, Optimization, Engine Performance

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1. Introduction

Alternative energy sources have directed scientists to research the sustainable energy such as biofuels. Petroleum based fuels have been consumed and harmful exhaust emissions from motored vehicles pollute the atmosphere. High-thermal efficiency diesel engines emit high amount of NO_x, CO and soot emissions [1-3]. This phonomena makes it obligatory to use new, environmentally friend alternative fuels. At this point, non-toxic biodiesel fuels seem to be effective in reduction of those exhaust emissions. Biodiesel has reasonable calorific value compared to diesel and the cetane number is higher than diesel fuel [3-6]. Biodiesel produced from vegetable and animal fat is biodegradable. Moreover, biodiesel fuels can be used without modification in diesel engines. Biodiesel has no sulfur in its chemical construction that sulfur combines with moisture in the air resulting in acid rains. On the other hand, oxygen content of biodiesel improves the chemical oxidation reaction [6-10]. Manríquez-Ramírez et al [11] prepared solid basic catalysts such as MgO–KOH, MgO–NaOH and MgO–CeO_2. They investigated the catalysts with SEM, XRD and FTIR spectrocopies. They have performed transesterification reaction at 60 ˚C with cooking oil and methanol. They have found that strength of the samples as MgO–KOH > MgO–NaOH > MgO–CeO_2. Wu et al. [12] developed a new production reaction system for biodiesel. They used bentonite as water adsorbent. They have seen th e effects of bentonite on NaOH-catalyzed methanolysis. The results showed that reasonable introduction of bentonite promoted the methanolysis. They have also seen that soap concentration lowered in crude biodiesel. McCarthy et al. [13] compared the performance and emission characteristics biodiesel fuel blends with diesel fuel. 80% tallow and 20% canola oil methyl ester and 70% chicken tallow and 30% waste cooking oil methyl ester fuel blends were experimented. They have found that engine performance decreased and specific fuel consumption increased for both biodiesel fuel compared to diesel. Verma and Sharma [14] investigated the effects of biodiesel such as soybean, jatropha, cottonseed, waste cooking oil on engine performance and exhaust emissions. They have realized that NO_x emissions increased for most biodiesel. However, HC, CO, and PM emissions decreased. They have also reported that B20 was the most suitable biodiesel fuel mixture. Çelikten [15] researched the effects of ethanol with rapeseed oil and soybean oil methyl esters and diesel. The tests showed that direct injection diesel engine can be operated with rapeseed oil or soybean oil methyl esters without modification. Smoke, CO and HC decreased while NO_x emission increased with the usage of biodiesel fuel blends. Kowalewicz [16] researched the effects of ethanol-diesel fuel mixtures and rapseed oil methyl ester-ethanol blends. He found that smoke and CO decreased with rapseed oil methyl ester. Pang et al. [17] observed the effects of biodiesel-ethanol-diesel experimentally. They stated that PM decreased, NO_x emission increased with the usage of fuel blends. Silitonga et al. [18] investigated the effects of Ceiba pentandra biodiesel on performance and emissions. Fuel blends such 10%, 20%,30% and 50% were preapred and experimented at different engine speeds. Test results showed that CPB10 presented best engine performance at full load condition. However, specific fuel consumption increased 22.98 % with CPB10 compared to diesel. They have demostrated that lower fuel blend increased the performance. Furthermore, they have seen that CO, HC and smoke opacity decreased with biodiesel fuel blens. Consequenly, they have emphasized that Ceiba pentandra biodiesel is suitable alternative fuel for diesel engines insted of diesel. Özdemir [19] investigated the effects of diesel+biodiesel+ethanol fuel blends on performance and emissions. Diesel+biodiesel fuel mixtures showed an increase on specific fuel consumption while decrease on brake torque and power output. Yılmaz et al. [20] investiagted the effects of neutralized waste cooking oil biodiesel-diesel blend (B10) in a direct injection diesel engine at different engine loads. According to test results, in-cylinder pressure and heat release rate increased with biodiesel fuel blend. CO and soot emissions decreased by about 28.21 % and %11.77 % respectively with B10 compared to diesel at full load condition. Aysal et al. [21] optimised the mustard oil biodiesel production process. Besides, the effects of mustard oil biodiesel-diesel fuel blends were tested experimentally in order to see the variations of engine performance parameters. As biodiesel fraction in the fuel mixtures increased, brake torque and power decreased, specific fuel consumption increased.

In this study, the effects of neutralized waste cooking oil biodiesel-diesel fuel blend (B30) were investigated on combustion, performance and emissions at 3.75, 7.5, 11.25, 15 and 18.75 Nm engine loads and 2200 rpm engine speed. The comparison has been also performed with neat diesel fuel. The aim of this study is to analyze combustion in a detail with B30 and compare the engine performance and exhaust emissions with diesel fuel. The variations of in-cylinder pressure, heat release rate, ignition delay, combustion duration, indicated mean effective pressure (imep) and CO, CO_2, NO_x and soot emissions were investigated in a diesel engine fueled with B30 and diesel test fuels.

2. Material and design

In this study, biodiesel was produced from neutralized waste cooking via transesterification method. NaOH was used as catalyst during biodiesel production process. Methanol was received from a commercial firm Merck. Molecular weight of methanol is 32.04 g/mol and density of methanol 0.791-0.793 kg/L at 20oC. Molecular weight of NaOH is 56.10564 g/mol and degree of purity is over the 97 %. Produced biodiesel was experimented in a diesel engine in order to see the effects on combustion, performance and emissions. The schematic view of the experimental setup is seen in Figure 1. The technical specifications of the test engine are also given in Table 1.

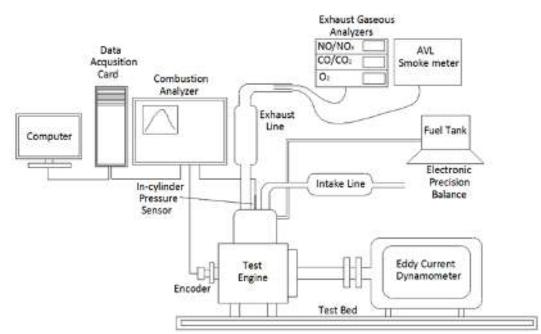

Fig. 1. The schematic view of the experimental setup

A single cylinder, four stroke, direct injection air cooled, normally aspirated Antor 6LD400 diesel engine was used in the experiments.

Cussons P8160 eddy current dinamometer which is rated 10kW at 4000 rpm engine speed was used in order to load the test engine in the experiments. Dynamometer can be also operated as motor. Engine load was varied by strain-gauge load cell. Engine speed is also controlled from the dynamometer control panel using potantiometer. AVL 8QP500c water cooled quartz in-cylinder pressure sensor was used in order to measure in-cylinder pressure.

In-cylinder pressure signals received from in-cylinder pressure sensor are amplified by Cussons P4410 combustion analyzer. Analog in-cylinder pressure signals are converted to digital signals using National Instrument data acqusition card. After then, digital in-cylinder pressure data were recorded in the computer. Encoder was adapted to the crankshaft of the test engine in order to determine the crank angle. Encoder produces 1000 pulses per revolution.

Table 1. The technical specifications of the test engine

Make / Model		Antor / 6LD400
Engine type		DI-Diesel engine, natural aspirated, air cooled
Cylinder number		1
Bore x stroke [mm]		86 x 68
Displacement [cm^3]		395
Compression ratio		18:1
Maximum power [kW]		5.4 @ 3000 rpm
Maximum torque [Nm]		19.6 @ 2200 rpm
Injection nozzle		0.24 [mm] x 4 holes x 160°
Nozzle opening pressure [bar]		180
Fuel delivery advance angle [ºKA]		24 BTDC
Valve timings	IVO / IVC [ºKA]	7.5 BTDC / 25.5 ABDC
	EVO / EVC [ºKA]	21 BBDC / 3 ATDC

So, in-cylinder pressure could be determined with the intervals of 0.36 °CA. In the experiments, B30 is obtained by mixing 30 % neutralized waste cooking oil biodiesel and 70 % neat diesel by vol. The chemical properties of the test engine are given in Table 2. The properties of the biodiesel were determined at Afyon Kocatepe University Automotive Engineering Department, Fuel Analysis Laboratory.

Table 2. The chemical properties of fuels [20-22]

	Diesel	Biodiesel
Calorific value [kJ/kg]	45343	38795
Density [kg/m^3 @15°C]	842	886
Flash point [°C]	47	173
Kinematic viscosity [mm^2/s]	2.98	4.65
Cetane number	>50	58

Testo exhaust gas analyzer was utilized in order to measure exhaust emissions such as CO, CO2, NOx. The technical specifications of the Testo exhaust gas analyzer are given in Table 3. Furthermore, AVL 4000 DiSmoke smokemeter was used in order to measure soot emissions. The technical properties of the AVL Di-Smoke 4000 smoke meter are given in Table 4. Heat release rate can be computed using in-cylinder pressure data. Heat release rate equation was determined based on the first law of thermodynamic. In addition, combustion stages, cyclic variations, combustion duration can be also calculated using in-cylinder pressure data.

Table 3. The technical specifications of the Testo exhaust gas analyzer

Combustion products	Operating range	Accuracy
O_2 [vol.%]	0–25	±2 mV
CO_2 [vol.%]	0–50	±0.3 vol.% +1 mV.% (0–25) vol.%) (0–25 vol.%)
HC [%]	0.01–4	<400 ppm (100–4000 ppm)
NO_x [ppm]	0–3000	5 ppm (0–99 ppm)

Table 4. The technical properties of the AVL Di-Smoke 4000 smoke meter

Analyzer	AVL DiSmoke 4000	
Measurement method	Partial flow	
	Opacity	K value
Operating range	0-100 %	Accuracy 0.1 %
Accuracy [m-1]	0-99,99	0,01

Heat release rate was computed with Eq (1) as seen below [23]. In-cylinder charge mass is assumed as an ideal gas. Besides, no gas leakages were accepted from the valves and piston rings.

$$\frac{dQ}{d\theta} = \frac{k}{k-1} P \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dP}{d\theta} + \frac{dQ_{heat}}{d\theta} \quad (1)$$

Cyclic variaitons also affects the engine performance which is important indication for stable operation. Cyclic variation should not exceed 10 % for stable combustion [23]. Cyclic variation can be calculated as follows. σ_{imep} defines the standard deviation of indicated mean effective pressure for consecutive 50 cycles and $\bar{X}$ defines the average of indicated mean effective pressures [23,24].

$$COV_{imep} = \frac{\sigma_{imep}}{\bar{X}} \times 100 \quad (2)$$

3. Results and discussion

Diesel engines can be operated with leaner charge mixtures resulting in lower CO and soot emissions. However, NO_x and soot emissions could not be reduced simultaneously. At this point, alternative fuels such as biodiesel are commonly used in the compression ignition engines. In this study, the effects of neutralized waste cooking oil biodiesel-diesel fuel mixture (B30) and neat diesel fuel were experimentally investigated and compared. So, combustion analysis and performance comparison were performed. Figure 2 shows the variations of in-cylinder pressure and heat release rate versus crank angle with test fuels at different engine loads. It was seen that maximum in-cylinder pressure and heat release rate were obtained with B30 for all engine loads. Higher oxygen content of biodiesel and reasonable calorific value resulted in higher in-cylinder pressure and heat release. Maximum in-cylinder pressure was obtained near the top dead center for all engine loads. Maximum in-cylinder pressure was retarded with the increase of engine load for both test fuels. More time is required in order to complete combustion with the increase of engine load, because more fuel is injected into the cylinder. Thus, combustion phasing is retarded at higher engine load. When Figure 2-e is examined, maximum in-cylinder pressure was obtained later according to other engine loads. Although in-cylinder volume is larger during combustion, higher maximum in-cylinder pressure was obtained. Maximum in-cylinder pressure should be obtained by about 10-12 ˚CA after top dead center versus crank angle in the internal combustion engines for better thermal efficiency [23,24]. It can be pointed that more injected fuel quantity caused to obtain higher in-cylinder pressure.

Figure 3 depicts the ignition delay versus engine load. Ignition delay time increases with the usage of B30. Similarly, ignition delay decreases with the increase of engine load. Higher engine load caused to obtain shorter ignition delay, because in-cylinder wall temperature is higher enough due to higher injected fuel in the combustion chamber. Lower calorific value and higher viscosity of B30 presented higher ignition delay compared to diesel. Especially higher ignition delay was obtained with B30 according to diesel as seen in figure 3. The fuels that has more viscosity values and higher density present higher ignition delay. Patel et al. [25] have found that higher ignition delay was found for KB20 (karanja biodiesel+diesel fuel) according to other test fuels. Ramkumar and Kirubakaran [26] emphasized that higher viscosity of biodiesel caused to obtain higher ignition delay compared to diesel and emit higher HC due to incomplete combustion.

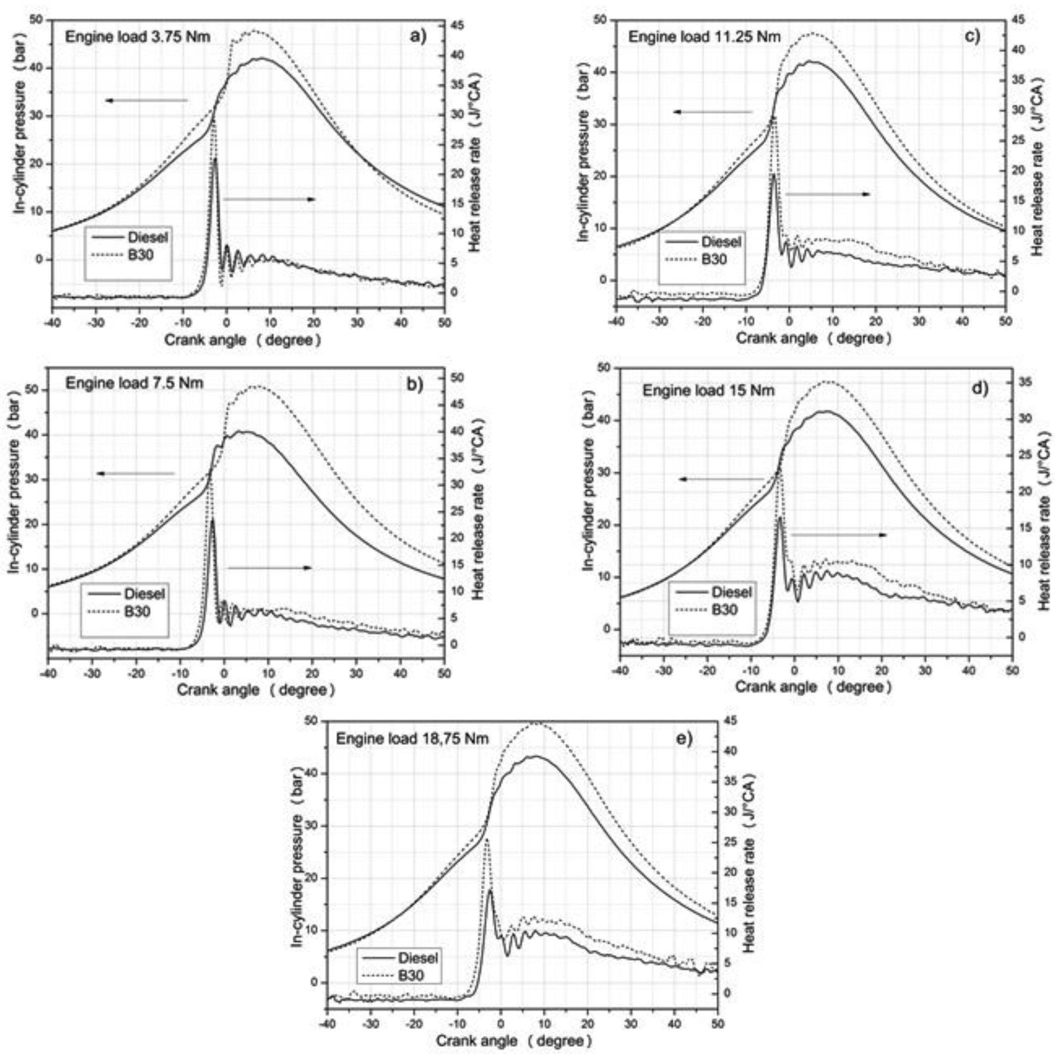

Figure 2. The variations of in-cylinder pressure and heat

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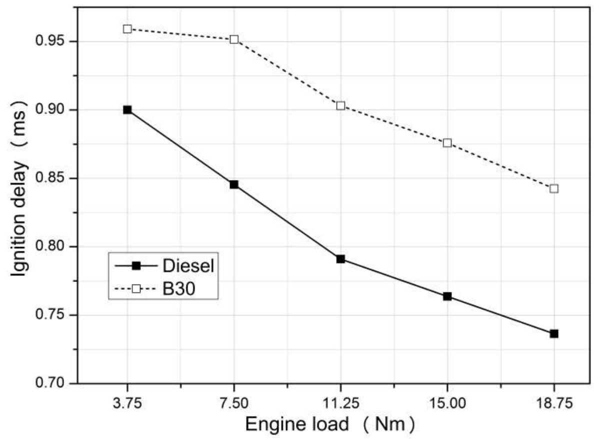

Figure 3. Ignition delay

Figure 4 shows the combustion duration with test fuels versus engine load. It was seen that combustion duration increased with the increase of engine load. The increase of injected fuel into the cylinder resulted in more time in order to complete combustion. In this study, CA10-90 was assumed to be combustion duration. The start of combustion is accepted as CA10 where the 10 % of charge mixture completed to combust versus crank angle. Chemical oxidation reactions improve with the addition of biodiesel into the diesel. Higher oxygen of B30 caused to better oxidation reactions. It can be said that fuel concentration of the charge mixture increases with the increase of engine load. As more fuel is injected, more combustion duration is required in order to complete combustion. Similar results were obtained with B10 biodiesel [20]. It can be also mentioned that higher cetane number of biodiesel decreased the combustion duration. Furthermore, there is more oxygen in biodiesels chemical construction that improves the oxidation reactions. So, combustion duration decreases compared to diesel. Figure 5-a and 5-b show the variations of CA10 and CA50. As expected, CA10 and CA50 increased with the increase of engine load, because more time is required in order to complete combustion for more fuel mixture. It was seen that more time is required for B30. Higher viscosity and density of biodiesel causes to obtaien higher CA10 and CA50. When Figure 5-b is examined, higher CA50 values were obtained with B30. It was also seen that CA50 was obtained nearly after top dead center with diesel compared to B30.

It can be stated that this situation causes to obtaien higher thermal efficiency with diesel. Thermal efficiency is an important indication that shows the converted heat energy from the fuel energy. Lower thermal efficiency was computed with B30 compared to diesel for all engine loads.

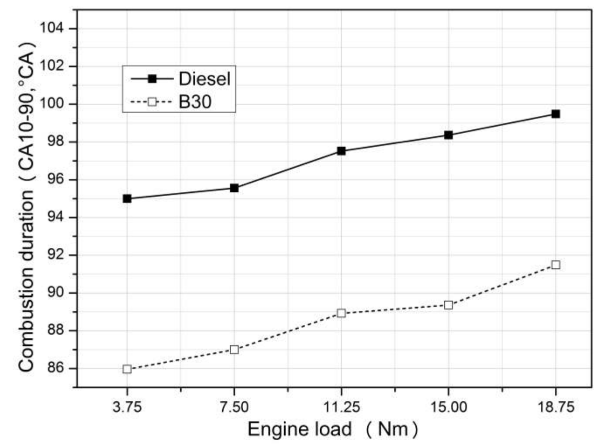

Figure 4. The variation of combustion duration

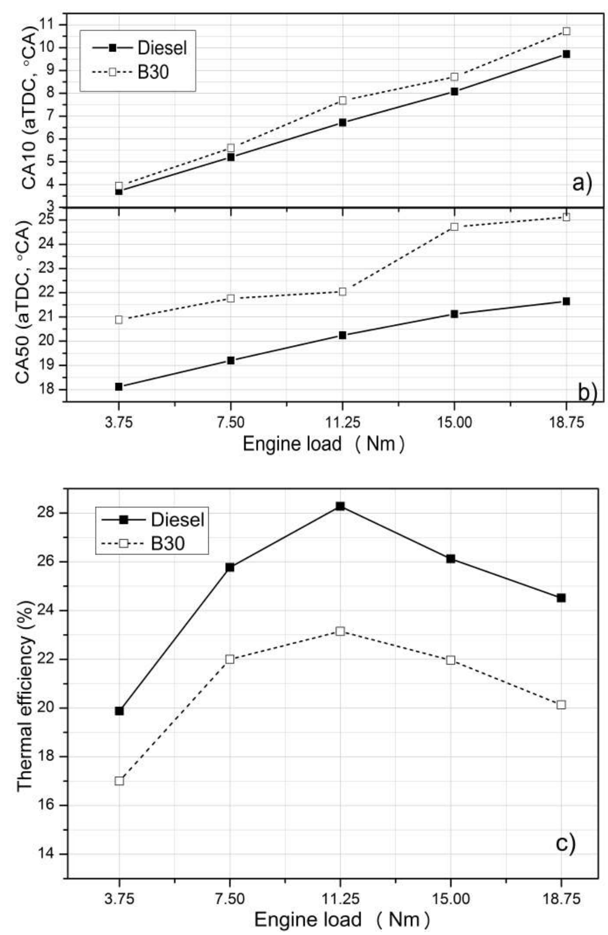

Figure 5.The variations of CA10, CA50 and Thermal efficiency

The highest thermal efficiency was obtained as 28. 3% at 11.25 Nm engine load. It was also found that higher calorific value of diesel leads to obtain highest thermal efficiency according to B30. Thermal efficiency increased until 11.25 Nm engine load and then started to decrease. Fuel concentration of charge mixture increases with the increase of engine load. Fuel molecules could not oxidize well in the combustion chamber. So, thermal efficiency decreases. Indicated mean effective pressure (imep) is another performance parameter without thermal efficiency. Figure 6 shows the imep values versus consecutive 50 cycle for both test fuels. As seen in Figure 6, higher imep values were obtained with B30 compared to diesel at 18.75 Nm engine load. Higher cetane number of biodiesel improves the evoparation and oxidation reactions. Besides, reasonable heating value of biodiesel caused to obtain higher imep compared to diesel. Combustion conditions in the combustion chamber are improved with higher cetane number and higher oxygen content of biodiesel. The thermodynamic situations and charge composition in the combustion chamber vary cycle to cycle. Cyclic variations should not be exceed 10% in the engine for stable operation [23]. Figure 7 defines the cyclic variations of imep versus engine load. Cyclic variations decrease as engine load increases. Higher fuel concentration of the charge mixture increased the in-cylinder temperature due to higher fuel molecules during combustion. This phonomena causes to improve oxidation reactions for the next cycle.

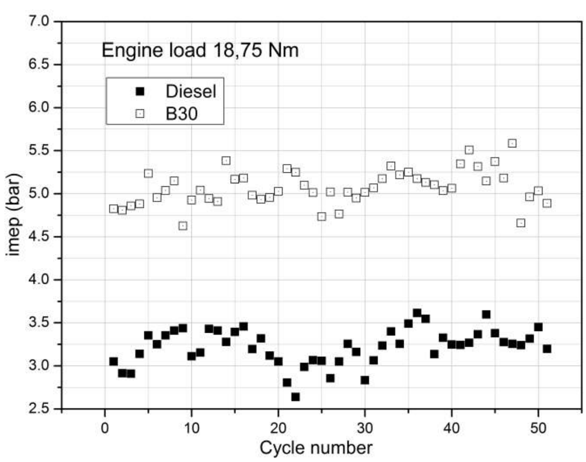

Figure 6. Imep versus cycle number at 18.75 Nm engine load

Moreover, higher cetane number of biodiesel provides the more stable combustion compared to diesel. Oxygen content of biodiesel also affects to obtain lower cyclic variations, because fuel and oxygen molecules could be easily reacted in the combustion chamber. So, cyclic variations reduced. It was also found that cyclic variation exceeds the 10 % with diesel fuel at 3.75 Nm engine load. At low engine load, in-cylinder temperature is not enough to occur better oxidation reactions. Unsufficient temperature and lower fuel quantity caused to obtain higher cyclic variation. At 3.75 Nm engine load, cyclic variation was obtained as 11.58 %.

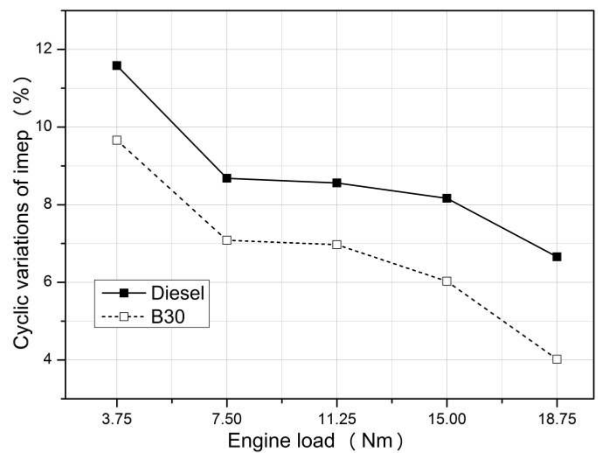

Figure 7. Cyclic variations of imep

Cumulative heat release is also analyzed in combustion analysis. Cumulative heat release gives information about mass fuel burned during combustion. In addition, cumulative heat release rate present the combustion stages ~~if~~ if it is normalized between 0 and 1. Figure 8 shows the cumulative heat release with test fuel at different engine loads. As expected higher cumulative heat release was obtained with B30 compared to diesel. It was also seen that cumulative heat release increased as increasing of engine load, because more fuel quantity is ignited resulting in more heat energy in the combustion chamber.

CO is harmful exhaust emission that is defined as incomplete combustion product. Unsufficient temperature and oxygen content in the combustion chamber prevents the chemical oxidation reactions. So, CO formation is seen. Lower CO can be obtained with biodiesel diesel engines [23]. Figure 9-a shows the CO variations of test fuels at different engine loads. Lower CO is seen with the usage of biodiesel, because oxygen content of B30 reduced the CO formation. It was also pointed that CO increased with the increase of engine load. The increase of engine load in a sense injected fuel caused to decrease of oxygen concentration in the combustion chamber. Highest CO was measured as 521 and 302 ppm for diesel and B30 respectively at 18.75 Nm engine load.

CO_2 are not accumulated in the atmosphere, because CO_2 released as a result of biodiesel combustion is used by its own vegetable [28]. Figure 9-b shows the CO_2 emissions versus engine load. There is an inverse relationship between CO and CO_2 as seen in Figure 9-a and Figure 9-b. CO_2 increased with the increase of engine load. Higher in-cylinder temperature caused to improve oxidation reactions due to more fuel at high engine loads. Conversely, CO_2 increased with the increase of engine load when the engine was operated with B30. The highest CO_2 was measured as 8.72 %, 7.6 % with B30 and diesel respectively at 18.75 Nm. One of the most important handicaps is that NO formation is seen in compression ignition engine due to higher in-cylinder gas temperature at the end of combustion.

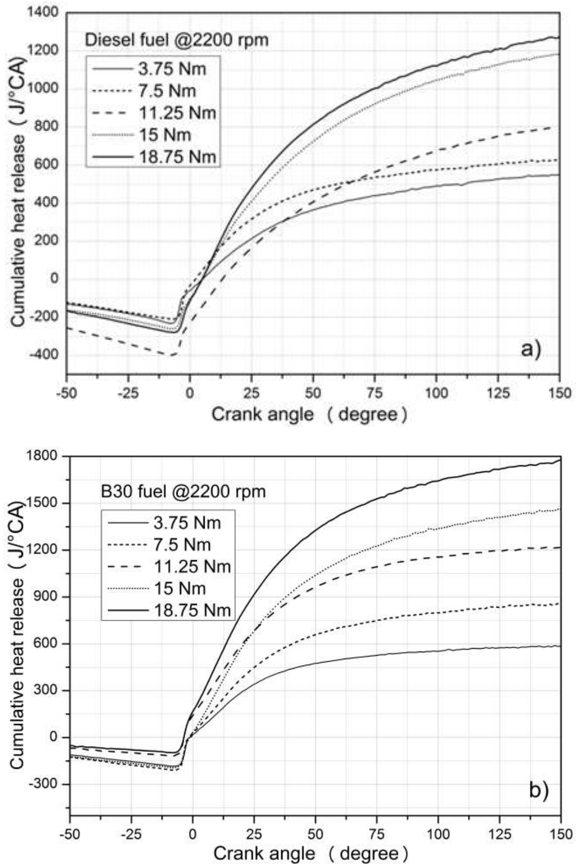

Figure 8. Cumulative heat release

Higher gas temperature is obtained in diesel engines that leads to react nitrogen and oxygen molecules resulting in NO formation. Figure 10-a shows the variation of NO_x versus engine load for test fuels. It was clearly noticed that higher NO_x was measured with B30 compared to diesel, because higher oxygen content of biodiesel caused to release higher NO_x. Maximum NO_x was measured as 782 and 582 ppm with B30 and diesel respectively at 18.75 Nm engine load. It was also seen that NO_x increased with the increase of engine load for test fuels. As more fuel is combusted, higher in-cylidner temperature is obtained at the end of combustion resulting in higher NO_x. Figure 10-b shows the soot emission versus engine load. Lower soot emission was obtained with B30 compared to diesel. It was also seen that the increase of engine load caused to release higher soot. Soot emissions are released due to partial combustion. It can be also explained that temperature decreases near the cylinder wall with the increase of fuel quantity. Thus, oxidation reactions deteriorate especially near the cylinder wall surface. Biodiesel has no sulfur resulting in lower soot.

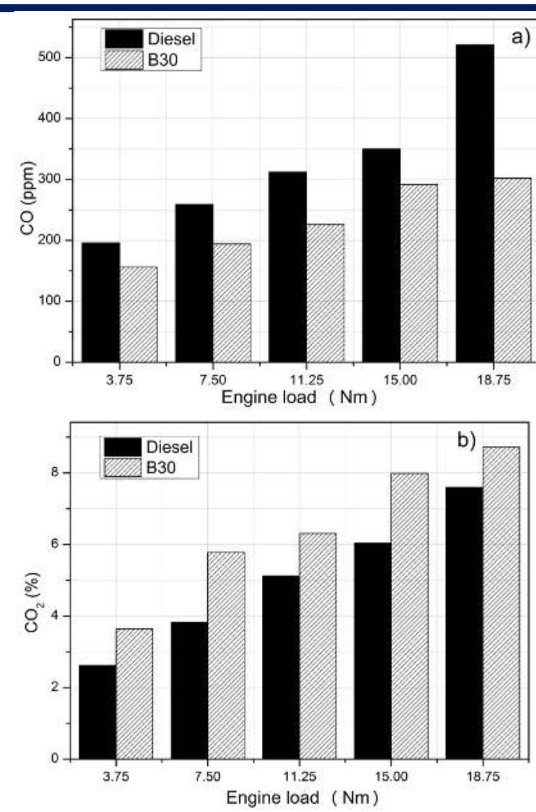

Figure 9. CO and CO_2 emission

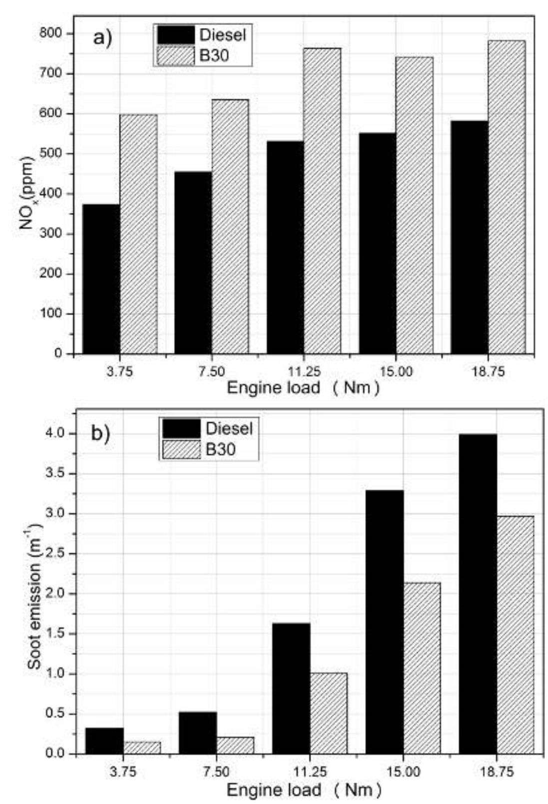

Figure 10. NO_x and soot emissions

Fuel concentration increased in the combustion chamber resulting in soot formation. The highest soot emission was measured as 3.99 m^{-1} and 2.97 m^{-1} with diesel and B30 respectively at 18.75 Nm engine load.

4. CONCLUSION

In this study, a single cylinder, four stroke, direct injection diesel engine was operated with neutralized waste cooking oil biodiesel-diesel fuel and neat diesel at different engine loads and 2200 rpm engine speed. The purpose of this experimental study is to investigate the effects of biodiesel on combustion, performance and CO, CO_2, NO_x and soot emissions. In addition, an experimental comparison was performed with neat diesel fuel. Test results showed that in-cylinder pressure and heat release rate increased with B30 compared to diesel. The increase of engine load caused combustion to retard. Shorter combustion period was obtained with B30. It was found that oxygen content of biodiesel improved the oxidation reactions compared to diesel. However, higher thermal efficiency was obtained with diesel due to higher calorific value of diesel. Thermal efficiency decreased by about 22.5 % with diesel fuel compared to B30 at 11.25 Nm. Significant reductions were seen on CO and soot emissions with B30 compared to diesel. However NO_x increased 34.3 % with B30 compared to neat diesel at 18.75 Nm. Cyclic variations decreased with the increase of engine load. Lower COV_{imep} was obtained with B30. In addition, COV_{imep} exceeds 10% with diesel fuel at 3.75 Nm engine load. It was seen that combustion and performance characteristics can be improved with biodiesel compared to diesel. As a result, neutralized waste cooking oil biodiesel-diesel fuel mixture (B30) could be easily used without engine modifications in diesel engine.

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