Performance and Emissions Characteristics of Biofuel Blend In a CI Engine

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Abstract
Chemical modifications of vegetable oils are made by catalyzed esterification with short chain alcohols, here methyl alcohol. In this study, methyl ester produced from sunflower oil, called as biofuel throughout the study, was blended with diesel fuel, 25% biofuel and 75% commercial diesel fuel, called here as biofuel blend; and used as a fuel in a direct injection diesel engine. The tested parameters were the engine power, torque, specific fuel consumption and exhaust gas emissions. The effects of using blend biofuel and diesel fuel in a direct injection diesel engine were compared to a baseline diesel fuel. The results have showed that performance of CI engine was good with the use of biofuel blend especially in comparison to diesel fuel, and exhaust emissions were reduced when using biofuel blend.

Keywords: Biofuel blend; Diesel engine; Performance; Exhaust emissions; Diesel fuel

1. Introduction

Energy conservation and alternative fuel researches are given high priority in energy planning in some countries. Because, the shortage of petroleum resources, environmental pollution due to these sources, and continuous increasing petroleum costs encourage new studies to develop alternative renewable fuels. At the same time, petroleum and its products are finite, and many scientists search to find alternative fuel to petroleum. The prevalence of internal combustion engines and subsequent developments in engine technology has led to widespread consumption of the petroleum fuels. Due to the shortage of petroleum products and its increasing cost, many efforts are put on the stage to develop alternative fuels, especially for fully or partial replacement of diesel oil. Many studies have been performed in developed countries and elsewhere, involving vegetable oils as a primary source of energy. The acceptability of vegetable oils as alternative diesel engine fuels was evaluated in the 1970s and 1980s because of the well known energy crises.

Chemical composition of vegetable oil is promising to be a suitable alternative for diesel fuel. Many works have been done involving vegetable oils as a primary source of energy. Particularly, during the early 1980's, many studies were completed about the possibility of using unmodified vegetable oils as diesel fuel. Using vegetable fuels in internal combustion engine is of special interest to countries without significant natural deposits of mineral oil. Recent petroleum crises, petroleum prices rose dramatically, increased the agricultural production cost. As the ignition quality and the calorific value of vegetable oils are generally similar to commercial diesel fuels, they would seem to provide an alternative.

Vegetable oils seem to have good potential as alternative fuels during period of fuel shortages and provide a sustainable and affordable energy source for rural energy demand in some developing countries. Vegetable oils that have been used as diesel fuel include sunflower, cottonseed, coconut, soybean, rapeseed, palm, jojoba, linseed, safflower, castor, olive, corn and rubber seed oils. Using vegetable oils as a fuel for diesel engines is not new. Indeed, some tests have proved similar engine performance and fuel consumption so far [1-14]. Due to some chemical and physical deficiencies vegetable oil was used as a blend with conventional diesel fuel with low percentages.

Since vegetable oils are all virtually sulphur-free, they create other problem in that they are generally too viscous, often acidic, they choke injector nozzles with carbon and leave high carbon residue on burning.

It has been shown that pure vegetable oils have harmful effects on engine parts and they cause a starting up problem. These are resulted from the higher viscosity of the vegetable oils. The problems due to the viscosity and density of the vegetable oils having different physical and chemical properties from of the diesel fuel should be eliminated to make them less viscous [15-18].

A great deal of research has been done about the blends with petroleum-derived diesel fuel. They have noted two problems as results of using vegetable oils and fuel blends. Firstly, a thickening of crankcase oil has occurred, which is attributed to the contamination of petroleum-based crankcase oil with unburned plant oil. And secondly, a build up of carbon on and in fuel injector nozzles was observed [19-24]. These problems manifest themselves in long-term use and have yet to be solved, and into the use of vegetable oil esters and emulsions. Ester or biofuel is an oxygenated diesel fuel that can be obtained from vegetable oils by conversion of the triglycerides to biofuels via transesterification [25-27]. Biofuel could be an excellent renewable fuel for diesel engines. It is derived from vegetable oils and fats that are chemically converted into biofuel. As the name implies, it is similar to diesel fuel except that it is produced from crops commonly grown in Turkey, including sunflower, cottonseed, soybean, nut and safflower.

Table 1. Physical properties of sunflower oil in comparison with other some vegetable oils

Properties	**Sunflower oil**	**Cottonseed oil**	**Soybean oil**	**Corn oil**
Density @ 26ºC (kg/lt)	0.918	0.912	0.92	0.915
Viscosity (mm^2/s) @ 26°C	34	33	33	35
Flash point (°C)	235	220	243	276
Calorific value (kJ/kg	39500	39600	39600	39550
Acid value	0.15	0.11	0.20	1.16
Cetan number	37	36	38	48
Cloud point	7.3	1.8	-4.3	-1.4

Physical properties of sunflower oil and some other vegetable oils are shown in Table 1. Chemical composition of sunflower oil indicates that this is a suitable alternative diesel fuel. Sunflower oil is attracting considerable attention as diesel fuel extenders of substitutes either in the form of the transesterified (chemically modified) sunflower oil with various monohydric alcohols [28]. Typical composition of sunflower oil and some other vegetable oils are shown in Table 2.

Table 2. Fatty acid composition of sunflower oil in comparison with other oils

Chemical Component	Carbon Bond	Chemical equation	Sunflower oil	Cottonseed oil	Soybean oil	Corn oil
Palmitic acid	16:0	C16H32O2	6	11	13	12
Stearic acid	18:0	C18H36O2	5	3	4	3
Oleic acid	18:1	C18H34O2	19	14	23	26
Linoleic acid	18:2	C18H32O2	69	57	56	58
Linolenic acid	18:3	C19H32O2	1	5	4	1

The reaction time of esterification is dependent on the boiling point, carbon number and the structure of the alcohol components. A similar processing may be performed on sunflower oil and alcohols. In case of methyl alcohol, the reaction may occur within the temperature range of 30–80ºC. It can be prepared to determine whether the esters or biofuel of these common fatty acids could be used as diesel fuels.

2. Experimental equipment and procedure

In this study, methanol with 1% sulfuric acid (H_2SO_4) is used for a fast transformation of free fatty acids into biofuel. Methanol to vegetable oil molar ratio is one of the important factors that affect the conversion efficiency of the process. Sulfuric acid is used as a catalyst in the acid-catalyzed pretreatment. A round bottom flask of 1,000 cm^3 is used as a laboratory scale reactor for the present analysis. Crude sunflower oil was dissolved in toluene, mixed with methanol with 2% H_2SO_4 in the flask, and kept in a 50ºC oil bath for 12 h. After the reaction is completed, the products are allowed to separate into two layers in the flask. The lower layer contains impurities and glycerol. The top layer, named ester (biofuel), is separated and purified using distilled water. The lower layer is discarded and the upper layer (purified biofuel) is separated. After the transesterification, it was bathed with hexane and drained from water with Na_2SO_4. Hence, the viscosity of biofuel is very close to diesel fuel. Chemical and physical properties of crude sunflower oil (CSO), biofuel (BF), diesel fuel, and the blend of biofuel and diesel fuel (biofuel blend) are shown in Table 3.

Table 3. Some properties of fuels used in the experiments

Properties	ASTM test no	CSO	Biofuel	DF	Biofuel blend
Density @ 26ºC (g cm^{-3})	D1298	0.918	0.89	0.84	0.86
Viscosity (mm^2 s^{-1}) at 26°C	D445	34	4.5	3.2	3.75
Flash point (°C)	D93	235	85	59	66
Calorific value (kJ kg^{-1})	D2015	39500	40500	42902	42301
Cetane number	D613	37	74	56	61
Molecular weight	-	858	845	360	481
Percentage of H (%)	-	11.88	11.95	15.10	14.31
Percentage of C (%)	-	76.93	76.69	83.26	81.61
Percentage of O (%)	-	11.19	11.36	-	2.84

Many engine performances and emissions tests have been conducted using biofuel or its blends. Results of these tests vary according to the base vegetable oil, the process of biofuel production as well as diesel fuel properties. In this study, tests were conducted at the Lombardini engine. The test engine technical data are listed in table 4. The test bed examination comprised the measurement of engine performance and of exhaust emissions.

Table 4. Lombardini Diesel Engine Details

Type	6LD 400 Lombardini
Number of cylinder	1
Cylinder diameter	86 mm
Stroke	68 mm
Clearance volume	395 cm^3
Compression ratio	18:1
Maximum speed	3600 l/min
Maximum power	6.2 kW @ 3600 l/min
Maximum torque	20 N.m @ 2200 l/min
Fuel tank capacity	4.3 lt
Oil consumption	0.0115 kg/h
Cooling	air
Injection timing	30 BTDC
Injection opening pressure	200 kg/cm^2
Starting	by dynamometer
Dry weight	45 kg

The tests were performed with maximum load and at different engine speed and engine power. Tests were performed on a laboratory test bed which consisted of a diesel engine, an electrical dynamometer, an exhaust gas analyzer, a data acquisition system, and engine mounting elements, as shown in Fig. 1.

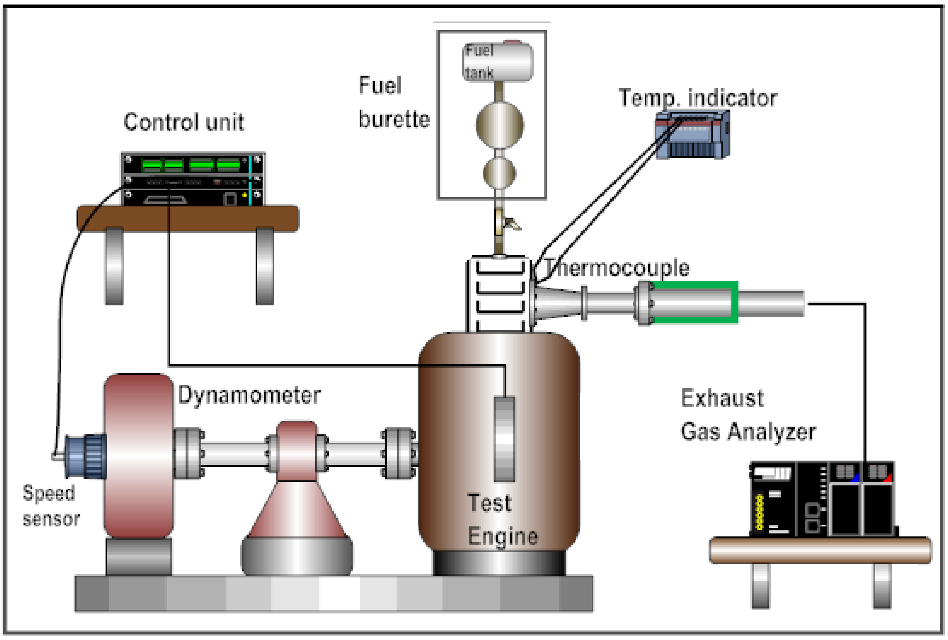

Figure 1. Schematic layout of the engine test system.

In this work, engine performance and various emission parameters such as CO, CO_2, NOx, O_2 exhaust temperature during combustion process under varying operating conditions with diesel fuel, and the blend of biofuel and diesel fuel were measured. The exhaust gas emission was measured using a gas analyzer apparatus. Percentages of carbon dioxide (%), carbon monoxide (ppm & mg/Nm^3), nitrogen oxide (ppm), nitrogen dioxide (ppm), sulphur dioxide (ppm & mg/Nm^3), oxygen (%), efficiency of combustion (%), and exhaust gas temperature (^{o}C) were determined by gas analyzer apparatus.

3. Results and discussion

3.1. Engine power

The power output at speeds between 1300 and 3100 rpm for diesel fuel and the biofuel blend were studied. The blend of biofuel and diesel fuel produced similar power outputs. Figure 2 shows the power outputs at various engine speeds. The power outputs during all speeds did not show any deterioration. In figure 2, the change of power at various engine speeds is plotted by line.

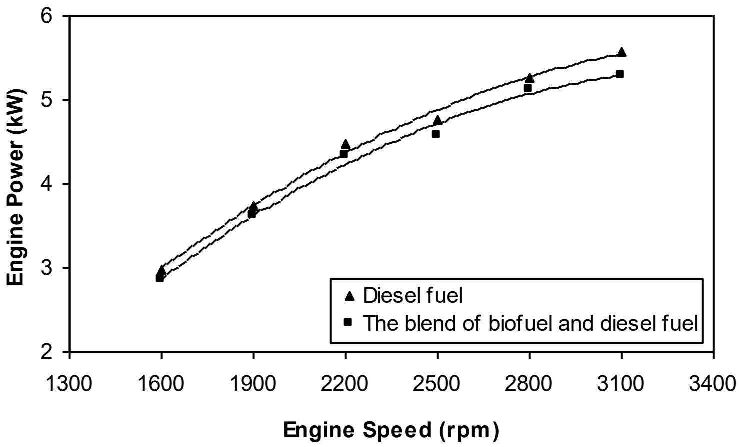

Figure 2. The variation of the engine power with engine speed for diesel fuel and the blend of biofuel.

The maximum power for both fuels occurred at 3100 rpm, with conventional diesel fuel producing a maximum power of 5.52 kW, followed by the biofuel blend, which showed a maximum power of 5.39 kW. The drop in engine powers between these two fuels was 1%. Combustion efficiencies are 90.4% and 89.6% for conventional diesel fuel and biofuel blend, respectively, at 3100 rpm. The powers obtained are related to the burning and fuels' heat capacities. The calorific value of conventional diesel fuel is 42902 kJ/kg, whereas that of the biofuel blend is 42012 kJ/kg, the difference in between them is approximately 2%.

3.2. Engine torque

In the experimental study, the engine was tested at full load and various engine speeds. Engine speed was first adjusted to 3400 rpm, and gas spindle was held constant at this speed. Then, the speed was decreased to 3100 rpm by loading the engine. By continuing the loading, the engine was run at the speeds of 2800, 2500, 2200, 1900, 1600, and 1300 rpm, respectively. The load obtained from the experiment was multiplied by torque rod length and the engine moment was calculated. Figure 3 shows the relations between engine speed and engine torque.

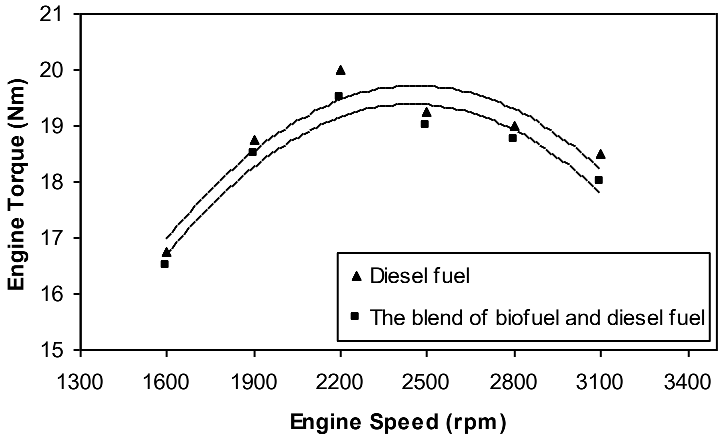

Figure 3. The variation of the engine torque with diesel fuel and biofuel blend at various engine speeds.

As seen in Figure 3, the maximum engine torque was obtained at 2200 rpm engine speed. The change observed at peak torque was similar at 2200 rpm. It was the same value stated in the engine's catalogue. A torque of 20 Nm was obtained with conventional diesel fuel at 2200 rpm, whereas with biofuel blend, a torque of 19.75 Nm was obtained. The decrease in the torque at 2200 rpm was nearly 1%. At the maximum engine torque speed, the combustion efficiencies are 93.3% and 89.9% for diesel fuel and the biofuel blend, respectively. The combustion loss is 2% between those two fuels. Torques of 17 Nm and 16.5 Nm were obtained with diesel fuel and the blend of biofuel, respectively, at 3100 rpm at maximum engine power. The drop in the torque is 3% at this speed.

3.3. The specific fuel consumption (SFC)

The specific fuel consumption (SFC) showed small differences at all engine speed values. Fuel consumption of an engine changes depending on engine speed and loading. Although the amount of fuel delivered into the combustion chamber in each cycle at a specific throttle valve position and engine speed are the same, the difference in densities of the fuels affects the amount of the fuel intake. That is because SFC is defined as the consumed fuel in mass per unit power. Variation of the SFC versus engine speed is shown in Figure 4. As seen in Figure 4, specific fuel consumption varies depending on the engine speed and the minimum SFC for both fuels was obtained at the maximum engine torque speed.

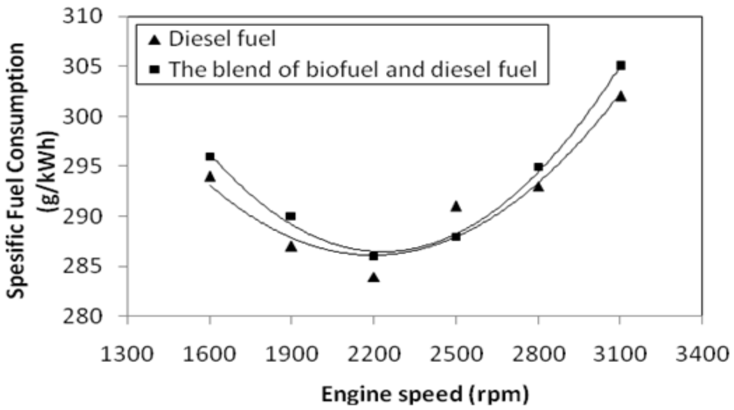

Figure 4. The variation of SFC with diesel fuel and biofuel blend at various engine speeds.

At high and low engine speeds, heat losses due to friction in the combustion chamber and deteriorating combustion increase SFC. Even if the volumetric fuel amount sent to the combustion chamber is the same in the case of the biofuel blend, SFC is higher, as the mass of the biofuel is higher and calorific value is lower. The specific fuel consumption was higher with the biofuel blend by aproximately 1–3 % as compared with conventional diesel fuel. The largest effect of high engine speed is the state of the fuel as it passes through the nozzle. The engine speed can be reduced to small amounts and leave the fuel emerging from the nozzle in mostly vapour state. The question that remains is the increase in the SFC at the high engine speed due to the deacrease in drop size and the calorific value or some other factors. The higher SFC for two fuels (the biofuel blend and conventional diesel fuel) are caused mainly by the lower heating values of the biofuel blend compared to diesel fuel.

3. 4. Exhaust Gas Emissions

3.4.1. Carbon monoxide (CO) emissions

Figure 5 shows the variation of CO emissions for both fuels with engine power. It is clear from Fig. 5 that CO emissions decrease with engine power and the biofuel blend produces significantly lower CO emissions than conventional diesel fuel. So the percentage of carbon monoxide of the biofuel blend was lower than diesel fuel. This was because better combustion took place in the engine fuelled with the blend of biofuel. CO is exerted as a result of inadequate burning and partial oxidation of carbon atoms in fuel. This emission changes depending on the air/fuel ratio in engine cylinder. When air/fuel ratio is small, the amount of CO emissions increases. When the air is insufficient, CO transforms to CO_2 after a certain amount of air. The CO concentrations in the exhaust were lower for the blend of biofuel operation compared to diesel fuel. The CO production was higher when running on the blend of biofuel at low engine power and was significantly reduced at high engine power.

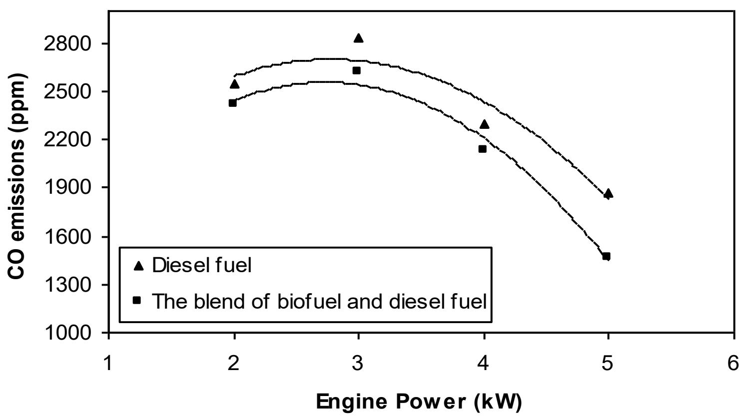

Figure 5. Comparison of CO emissions of the blend of biofuel and diesel fuel at various engine powers.

As can be seen from CO emission–engine power relation, CO emission tends to decrease with the increase in engine power. When OH (hydroxyl radical) radical, which transforms CO to CO_2, decreases below 1500°K, burning deteriorates and, consequently, the amount of CO increases due to the lower temperature [29]. Since turbulence occurs in the combustion chamber at higher engine speed and power, burning improves, and due to the increase of the temperature of the mixture, CO emission decreases. As the engine power decreases and the loading increases, the quality of burning gets worse and CO emission rises. It was found that CO concentration was up to 10% less when the engine burnt the biofuel blend, compared to 100% conventional diesel fuel. These findings are useful to gain an understanding of the emissions and environmental impacts of the biofuel blend.

3.4.2. Carbon dioxide (CO_2) emissions

The variation of CO_2 emissions with the biofuel blend and conventional diesel fuel are shown in Fig. 6. Carbon dioxide emission is an emission product related to the entire combustion of the fuel. High post-combustion temperature and existence of enough oxygen for an exact burning increases the amount of carbon dioxide. Carbon Dioxide is an odorless, colorless non-flammable gas and is the most prominent greenhouse gas in Earth's atmosphere. Fossil fuels contain carbon, and when they are burned, they combine with oxygen and form carbon dioxide. The World Energy Council reported that global carbon dioxide emissions from burning fossil fuels rose 12% between 1990 and 1995. The Commission White Paper European policy predicts that by the year 2010, the CO_2 emissions from transport will have risen to about 1113 million tons annually with the main responsibility resting on road transport, which accounts for 84% of the transport related carbon dioxide [30].

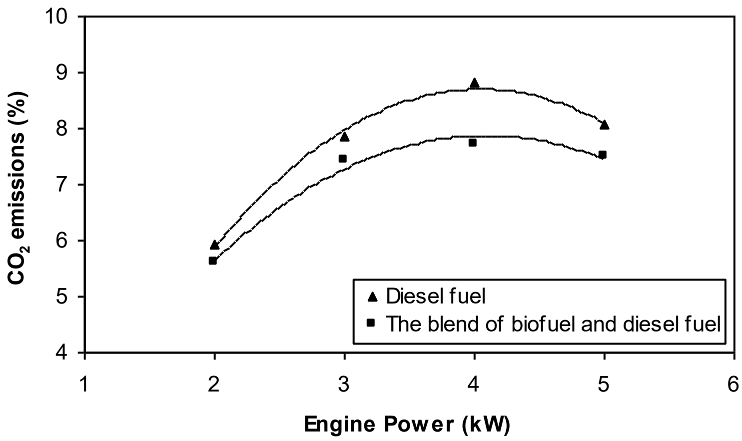

Figure 6. Comparison of CO_2 emissions of the blend of biofuel and diesel fuel at various engine powers.

The carbon dioxide increased with increasing engine power. It was also found that with the carbon dioxide percentage of the biofuel blend was lower compared to diesel fuel. There was very little difference between CO_2 emission when running the blend of biofuel and diesel fuel and diesel fuel at low engine power.

3.4.3. Nitrogen oxide (NOx) emissions

In Figure 7, NOx emissions and engine power graphics are seen. As seen in Figure 7, initially the increase in NOx emission for both fuels with the increase in engine power increases and then decreases.
The conversion of nitrogen and oxygen to NOx is generated by the high combustion temperatures occurring within the burning fuel sprays and is controlled by local conditions. NO_x is a collective term used to refer to nitric oxide (NO) and nitrogen dioxide (NO_2). The nitrogen oxides in exhaust gases are formed through the reaction between nitrogen and oxygen. The two factors that most significantly influence the formation of NOx are temperature and oxygen concentration – the higher the temperature and the longer the residence time at high temperatures in the cylinder, the greater the amount of NOx that is generated. Combustion processes produce nitrogen oxides from nitrogen in the air and to a small extent from nitrogen in fuels. Its formation is dependent on the duration of the flame temperature in the combustion chamber above 1800°K [31]. When the burning temperature is above 1800°K, NOx formation considerably accelerates. NOx formation changes depending on the air surplus coefficient.

When air surplus coefficient is higher, the cooling rate of the engine decreases and the exhaust system remains hot. In lean mixtures, first O_2 is decomposed to 2O. Then, NO is formed from free radicals. As explained in Zeldhovich mechanism, NOx formations are:

$O + N_2 \leftrightarrow NO + N$ and $N + O_2 \leftrightarrow NO + O$

Later in the process, during expansion and in the exhaust system, part of the NO is converted to NO_2 and N_2O (nitrous oxide), typically, 5% and 1%, respectively, of the original. If the fuel contains nitrogen, and some residual fuels contain as much as 1%, then all or part of this nitrogen will also oxidize to form NOx [30].

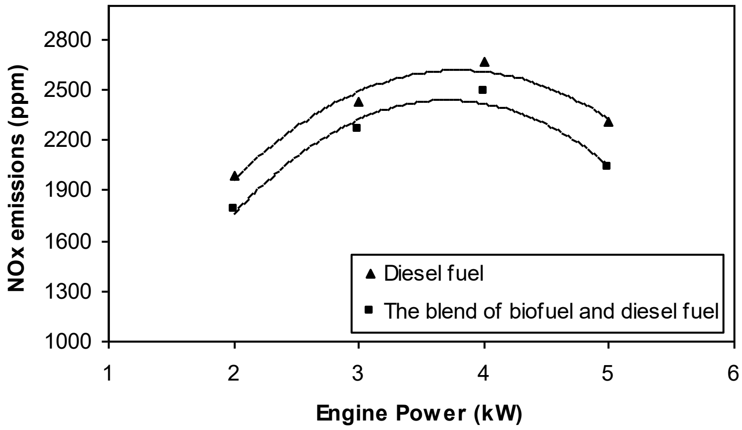

Figure 7. Comparison of NOx emissions of the blend of biofuel and diesel fuel at various engine powers.

Since the activation energies of these reactions are high, both reactions in lower temperatures are very slow. Regarding this, the amount of oxygen, which determines the reaction rate at lower temperatures, can be neglected. At the temperature in the burning fuel sprays, nitrogen is no longer inactive, and oxygen and nitrogen react to form oxides of nitrogen. The immediate reaction is the formation of NO. As can be seen from Figure 7, initially the increase in NOx emission is for both fuels with the increase in engine speed and then the decrease after the maximum torque speed. From both graphics of emissions, it is seen that the best burning is in the maximum torque range. This also means that the maximum temperature is reached in this range and NOx emissions are higher.

4. Conclusions and recommendations

In this study, the biofuel was synthesized from crude sunflower oil through a transesterification process, and this fuel blend was used in a four-stroke diesel engine in order to determine if it could be used as an alternative fuel for diesel engine. According to the results obtained from this work, the following conclusions can be drawn:

1. The blend of synthesized biofuel had more similar properties to those of conventional diesel fuel compared with crude sunflower oil. In particular, the viscosity of the biofuel considerably decreased as the result of esterification. So blend of 25% biofuel with 75% conventional diesel fuel can be used in unmodified diesel engines.
2. When engine performance was taken into consideration, there were slight decreases in the engine torque and power with respect to conventional diesel fuel. The variation of power, depending on the engine speed, was found to be 1 – 2%. The main reason for this decrease was considered to be poor atomization or inadequate burning due to the lower heat capacity and high viscosity.
3. In the case of biofuel blend, specific fuel consumption was higher than conventional diesel fuel. The difference varied in the range of 1 – 2% depending on the engine power. This was due to the lower heat capacity and higher density of biofuel blend.
4. CO and CO_2 emissions measured with conventional diesel fuel were higher than those with biofuel blend for all the engine powers. The same results were valid for NOx emission. NOx and CO_2 emissions were high in the range of maximum burning efficiency. When exhaust emissions are considered, it can be concluded that biofuel blend is better than conventional diesel fuel.

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