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INVESTIGATION OF THE EFFECTS OF BIODIESEL-DIESEL FUEL BLENDS ON THE PERFORMANCE AND EMISSION CHARACTERISTICS OF A DIESEL ENGINE

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Abstract

The growing demand of diesel power generators in Iran has led to air pollution. Hence, it is necessary to ascertain the level of performance and emissions of the diesel power generators fueled with biofuels. For the first time, in this study, the effect of biodiesel from waste cooking oil and diesel fuel blends (B0, B20, B50, B80 and B100) on the performance (brake power, brake torque, BSFC, brake thermal efficiency and exhaust gas temperature) and emission characteristics (CO and NOx) of a diesel power generator model CAT3412 was investigated. The experiments were conducted at rated engine speed 1530 rpm and various engine loads (25%, 50%, 75% and 100%). The results of the study showed an increase in brake power, brake torque, BTE and NOx emission and a reduction trend in BSFC and CO emission at higher engine loads for all the biodiesel-diesel blends. In addition, the research results indicated that B20 and B50 fuel blends in terms of performance emission characteristics could be recognized as the potential candidates to be certificated for usage in the diesel power generator.

Keywords: Biodiesel, Performance, Emission, Diesel Power Generator, Engine Load

1.0 INTRODUCTION

Today, fuels derived from crude oil such as alcohols and biodiesel have been the major source of the world's energy as well as transportation sector due to environmental and energy concerns [1-4]. The fuel properties of biodiesel may be changed when different feedstocks are used. If the fuel properties of biodiesel are compared to petroleum diesel fuel, it can be seen that biodiesel has higher viscosity, density, pour point, flash point and cetane number, near-zero aromatic compound, and no sulphur link [5]. Biodiesel fuel has many effects on diesel engine performance. There has been a lot of research on the regulated performance characteristics of diesel engines with biodiesel/diesel blends.

There are many literatures to study the effect of pure biodiesel on engine power, and most of them agreed that, with biodiesel (especially with pure biodiesel), engine power will drop [6-12]. Hansen *et al*. [13] observed that the brake torque loss was 9.1% for B100 biodiesel relative to D2 diesel at 1900 rpm. Of course, it was reported that there were surprising increases in power or torque of engine for pure biodiesel [14, 15]. Song and Zhang [14] observed that the engine brake power and torque increased with the increase in biodiesel percentage in the blends. But it is the most unbelievable that the increased power of the pure biodiesel could reach 70% relative to diesel fuel [15].

For BSFC, Many researches compared the blends with different content biodiesel. Most of them [10, 12, 16-21] agreed that the fuel consumption of an engine fueled with biodiesel becomes higher. In some studies [12, 18, 22-24]authors believed that with increasing the content of biodiesel, engine fuel consumption will increase. On the contrary, it was reported that fuel consumption was decreased for biodiesel compared to diesel [14, 25-27].

According to some researches [8, 28-37], the use of biodiesel from soybean oil, palm oil or residual frying oil increases the specific consumption of the diesel engine. Only five papers [31, 33, 34, 37, 38] point the decrease of this aspect due to the use of biodiesel. Other papers [28, 29, 32-35, 37] indicate that the increase of the biodiesel percentage in the blend increases the specific fuel consumption.

However, Xue *et al.* [37] indicates the decrease of specific fuel consumption occurs with the increase of engine speed, from1000 rpm to2000 rpm, when use residual palm frying oil. Also, another study from the same paper indicates that the lowest specific consumption value was observed at the electrical load of 50kW, when use the same biodiesel. Also, Sadeghinezhad *et al.*[38] indicates that the use of residual frying oil reduces the specific fuel consumption by 2.43%, for a 4-cylinder, 4-stroke diesel engine with 46kW.

Enweremadu and Rutto [34] reported the specific fuel consumption of B100 is 4% higher than that for diesel, under loaded condition. The specific fuel consumption slightly increases per kWh with increasing the percentage of biodiesel from residual frying oil on the blend. In the study, which is indicated by Enweremadu and Rutto [34], shows that minimum values of specific fuel consumption are obtained at1750rpm.The biodiesel from residual frying oil presents 258.66g/kWh of specific fuel consumption, against 229.59g/kWh for diesel.

Banapurmath *et al*. [39]compared the effect of three injection timings and the different injection of pressure (IOP) on the brake thermal efficiency (BTE) for Honge oil methyl ester. They found that there was an improvement in the BTE for biodiesel by retarding injection timing, and that the highest BTE occurred at 260 bar among all the IOPs tested because atomization, spray characteristics, and mixture with air were better with higher injection, which result in improved combustion. And, Sharma *et al*. [40]concluded that the difference of BTE between biodiesel and pure diesel tended to increase with the increase of fuel injection pressure. Carraretto *et al*.[41] observed that power and torque were increased up to almost pure diesel levels by reducing injection advance because it was possible to optimize combustion, and by improving performances especially at low and medium speed with respect to nominal injection advance operation.

In the comparative study, combustion characteristics and brake thermal efficiency of a diesel engine fueled with diesel and biodiesel (FAME100%) were conducted. The results of the research showed a decrease of about 0.6% in BTE of the engine by fuelling the heavy-duty diesel engine with biodiesel. Meanwhile, increases of approximately 2%, 17% and 11% in BSEC, BSFC and volumetric BSFC were observed.

In addition, Ferreira *et al*.[42] presented an analysis of additional ethanol injection on performance and emissions a diesel engine powered with a blend of diesel-biodiesel. The tests were made in an engine at 1800 rpm, connected to an electric generator. In this research the energy analysis showed a decrease in engine efficiency with the addition of ethanol. And also it was proven that the ethanol addition can be an important method to reduce the amount of NO_x in the exhaust gases of diesel engines.

The impacts on fuel consumption and exhaust emissions of a diesel power generator operating with biodiesel were investigated by Valente *et al.* [43]. They found that fuel consumption increases with higher biodiesel concentration in the fuel. Also soybean biodiesel blends showed lower fuel consumption than castor biodiesel blends at a given concentration. Other finding in this study was that at low and moderate loads, CO emission was increased when fuel blends containing 35% of castor oil biodiesel or soybean biodiesel were used, in comparison with diesel oil and besides with the load power of 9.6 kW, the use of fuel blends containing 20% of castor oil biodiesel or soybean biodiesel increased HC emissions by 16% and 18%, respectively, in comparison with diesel oil.

The growing demand of diesel power generators in Iran has led to air pollution. On the other hand there has been no study done about the effects of biofuels on the performance and emission characteristics of the diesel power generators in Iran particularly used in National Iranian Drilling Company. Hence, in this study, the performance and emission characteristics of biodiesel blended with diesel fuel No.2 in ratios of 0%(B0), 20%(B20), 50%(B50), 80%(B80) and 100%(B100) was investigated for a diesel generator engine under four engine loads (25%, 50%, 75% and 100%) at the rated engine speed of 1530 rev/min for the first time.

2.0 EXPERIMENTAL

2.1 Biodiesel Properties

Since biodiesel from waste vegetable cooking oil is a more economical source of the fuel in the present investigation, in this research, biodiesel from this source was used [4, 44].

In the present research, biodiesel was purchased from Tarbiat Modares University (TMU) biofuels laboratories (lab.) In this lab,biodiesel is produced by a transesterification process which was catalyzed by KOH (as Alkali catalyst) and methanol (as alcohol). Then, biodiesel was analyzed by an established research institution following the ASTM D6751 standard. The important properties of waste vegetable cooking oil and No. 2 diesel are shown in Table 1.

2.2 Test Engine Experimental Setup, Procedure and Performance and Emission Characteristics Calculation

In this study, the engine tests were carried out on a diesel power generator model CAT3412 consisting of a four-stroke, supercharged diesel engine coupled to an instrumented generator to evaluate the engine performance characteristics. The generator was equipped with a central processing system and a control panel to record the data. Also a system with scale method was used to for determination of engine fuel consumption. Exhaust gas temperature and exhaust emissions were measured by using K type thermocouples and AVL exhaust gas analyzer respectively.

The major specifications of the internal combustion engine are shown in Table 2. The characteristics of the generator are: maximum power – 330kVA; voltage – 380V; three-phase; rotation – 15300rpm, Armature rotor resistance–0.1 Ω, and Stator resistance–0.15 Ω. Also the power factor of 0.90 was used. Figure 1 shows the diesel power generator. The diesel engine was fuelled with blends of biodiesel and No. 2 diesel fuel. The fuel blends were used at the constant engine speed and different electrical load. The engine was allowed to run for a few times until the exhaust gas temperature, the cooling water temperature, the lubricating oil temperature have attained steady-state values and then the data were recorded. In this research, Armature rotor resistance and stator resistance were considered to calculate of engine brake power. The matrix of experimentation is shown in Table 3. Based on the engine brake power, the engine speed and the mass consumption rate of the fuel, the brake torque, the brake specific fuel consumption (BSFC), the brake thermal efficiency (BTE), exhaust gas temperature, CO and NO_x emissions were calculated.

Table 1 Properties of diesel and biodiesel fuels used for present investigation

Property	*Method*	*Units*	*Limits*	*Biodiesel*	*Diesel*
Flash point	ASTM-D92	°C	130 Min	182	64
Pour point	ASTM-D97	°C	------	-3	0
Cloud point	ASTM-D2500	°C	------	0	2
Kinematical viscosity, 40°C	ASTM-D445	mm^2/s	1.9-6	4.15	4.03
Copper strip corrosion	ASTM-D130	--------	No. 3 max	1a	1a
Density	---------	Kg/m^3	------	880	840
Lower Heating Value	---------	MJ/kg	------	37.7	42.9

Table 2 Specifications of the test engine

Engine type	**Diesel power generator CAT3412**
Cylinder number	12
Stroke(mm)	154
Bore(mm)	137
Compression ratio	13: 1
Cooling system	Water cooled

Table 3 The matrix of experimentation

Parameters	**Levels**				
	1	**2**	**3**	**4**	**5**
Speed (rpm)	1530	-	-	-	-
Load (%)	25	50	75	100	-
Biodiesel (%)	0	20	50	80	100
Diesel fuel (%)	100	80	50	20	0

Figure 1 The engine test set up

3.0 RESULTS AND DISCUSSION

3.1 Brake Power

The brake power amounts for different fuel blends are shown in Figure 2. As the Figure shows the maximum brake power is 130 kW for the fuel blend included 50% biodiesel at full engine. Also the minimum brake power (24.8 kW) happens at 25% engine load for B100.

As shown in Figure 3, the brake power decreases with increasing the amount of biodiesel in fuel mixture for B80 and B100. Probably, the main reason for the higher brake power amounts of diesel fuel No.2 than that of B80 and B100 in lower engine loads could be due to the lower heating value of biodiesel [6-8, 10-12, 45].The fuel flow problems as higher density and higher viscosity of biodiesel and decreasing combustion efficiency as bad fuel injection atomize than diesel fuel also have certain effects on decreasing brake power [6, 10].

On the other hand, it can be understood from the percentages, the brake power level increased with the proportion of biodiesel for B20 and B50. Also the value of the brake power for pure diesel is less than that of other blends in higher loads. These results are due to the higher oxygen content of biodiesel in combustion region that provided more complete combustion. This means that biodiesel in the fuel mixture increases oxygen content of the blend; that causes higher combustion efficiency especially in higher loads and compensates the loss of heating value of biodiesel for these fuel blends [5, 46]. In addition the engine delivers fuel on volumetric basis and biodiesel density is higher than that of diesel, which supplies more biodiesel to compensate the lower heating value [47].

As shown in Figure 2 the brake power of the engine is relatively high at higher engine loads, because the increase in combustion temperature leads to more complete combustion during the higher load [8]. Also at higher engine load, a beneficial effect of biodiesel as an oxygenated fuel was seen to generate more complete combustion, which means increased brake power. This indicates that the addition of oxygenated fuel is most effective in rich combustions [12, 48].

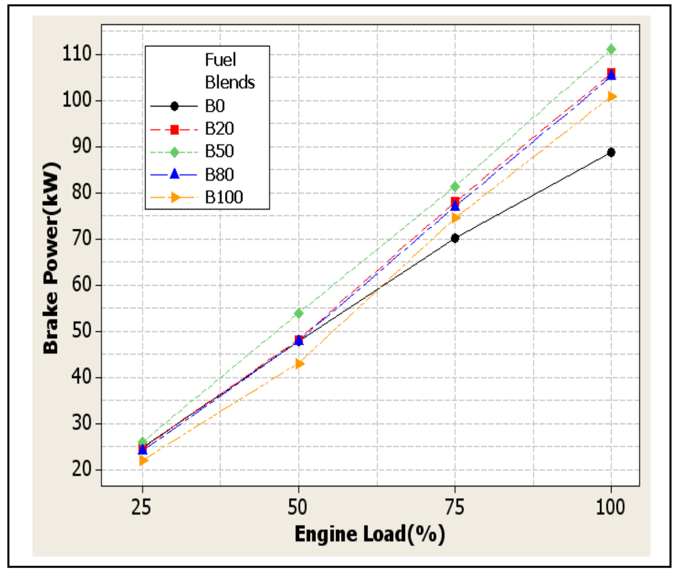

Figure 2 Effect of fuel blends on brake power at various engine loads (brake power values given are means ± 1.4Kw as standard error)

3.2 Brake torque

Figure 3 shows the effects of biodiesel percentage and engine load on the brake torque of the engine at constant engine speed. As the figure shows the maximum brake torque is 812 N.m for the fuel blend included 50% biodiesel at full load. Also the minimum brake torque (155 N.m) happens at 25% engine load for B100.

The values for the brake torque trends to decrease by increasing biodiesel proportion in fuel mixture for B80 and B100. These decreases are understandable, since the heat content of the fuel blend decreases with the increasing amount of biodiesel compared to that diesel fuel No.2 [7, 10-13, 45, 49].

On the other hand, the brake torque level increased with the proportion of biodiesel for B20 and B50 due to high lubricity and the higher oxygen content of biodiesel. As shown in Figure 4 the value of the brake torque for pure diesel is less than that of other blends in higher loads. These properties might result in the reduced friction loss and more complete combustion and thus especially improve the brake effective torque in higher loads and compensates the loss of heating value of biodiesel[17].

Also Figure 3 shows the brake torque increases with increasing engine load, because the increase in combustion temperature leads to more complete combustion during the higher load [8].

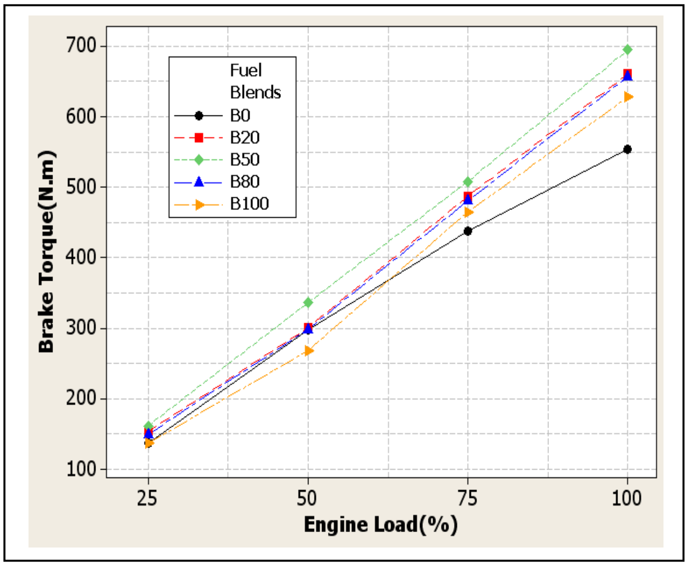

Figure 3 Effect of fuel blends on brake torque at various engine loads (brake torque values given are means ± 5.7 as standard error)

3.3 Brake Specific Fuel Consumption

Figure 4 shows the effects of biodiesel percentage and engine load on the brake specific fuel consumption of the engine at engine speed of 1530 rpm. As the Figure shows the maximum brake specific fuel consumption is 1057 (gr/Kw.hr) for the fuel blend B100 at 25% engine load. Also the minimum brake specific fuel consumption (210 (gr/Kw.hr)) happens at full engine load for the fuel blend included 20% biodiesel.

The values for the brake specific fuel consumption increase with the increasing amount of biodiesel in the fuel blends B80 and B100. The heating value of the biodiesel is lower than that of diesel fuel No.2. Therefore, if the engine was fueled with biodiesel or its blends, the BSFC will increase due to the produced lower brake power caused by the lower energy content of the biodiesel [5, 7, 10, 12, 17, 45, 50]. At the same time, for the same volume, more biodiesel fuel based on the mass flow was injected into the combustion chamber than diesel fuel No.2 due to its higher density. In addition to these parameters, viscosity, the atomization ratio and injection pressure should be considered since they have some effects on the BSFC and brake power values [14, 46]. On the other hand, the BSFC of B20 and B50 is less than B0 because of the higher oxygen content of biodiesel that improves the brake power and compensates the loss of heating value of biodiesel[5, 17].

As the figure shows with increase in load, the BSFC of biodiesel decreases. One possible explanation for this trend could be the higher percentage of increase in brake power with load as compared to fuel consumption [12, 17-21, 51].

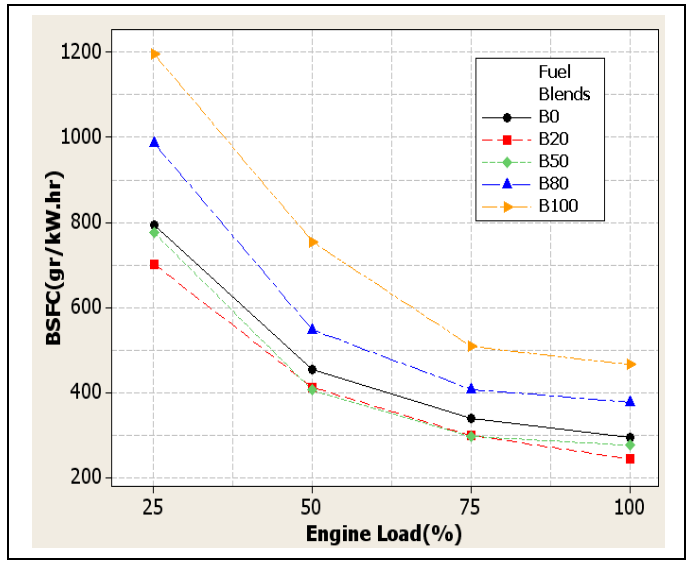

Figure 4 Effect of fuel blends on BSFC at various engine loads (BSFC values given are means ± 14 as standard error)

3.4 Brake Thermal Efficiency

Brake thermal efficiency of a diesel engine is the efficiency in which the chemical energy of a fuel is turned into useful work [52]. It can be determined by dividing the useful work by the lower heating value of the fuel. Also can be simplified and indicated in the Eq. (1)[7]:

$$\eta_{th} = \frac{3.6\times10^6}{H_{LHV}\times BSFC} \quad (1)$$

The brake thermal efficiencies (BTE) of the engine fuelled with diesel, B20, B50, B80 and B100 fuels are shown in Figure 5. B20 gives the best brake thermal efficiency of engine with the value 40.4% at full engine load. Also the minimum brake thermal efficiency (8.1%) happens for B100 at 25% engine load. As seen in Eq. (1), the thermal efficiency has inverse relationship with the BSFC and lower heating value (H_{LHV}). Therefore, the primary reason for the decrease in the brake thermal efficiency of the fuel blends included 80% and 100% biodiesel than other blends is the higher BSFC in spite of lower energy content of biodiesels.

According to the Figure 5, it can be shown that the BTE of the engine is higher for B20 and B50 than that of B0. This improved efficiency was explained by some authors with more effective combustion and increased lubricity of these blends as compared to diesel fuel [5, 17]. In all cases, brake thermal efficiency has the tendency to increase with increase in applied load. This is due to the reduction in heat loss and increase in power developed with increase in load[17].

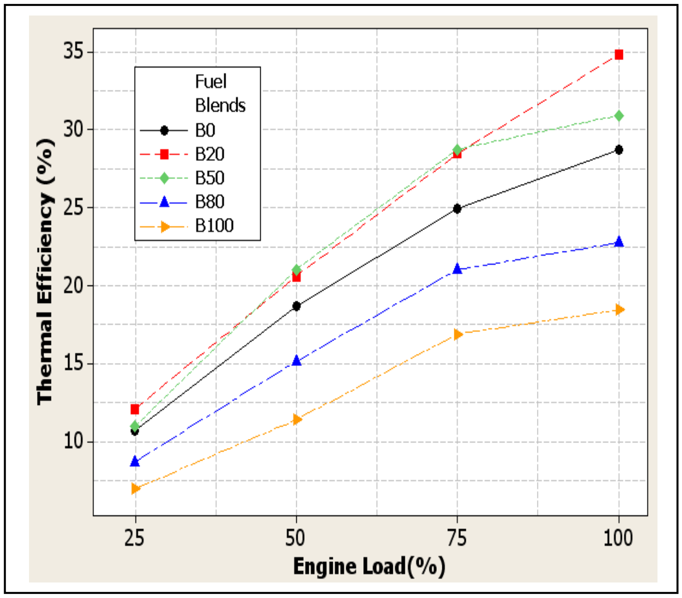

Figure 5 Effect of fuel blends on brake thermal efficiency at various engine loads (BTE values given are means ±1.06 standard error)

3.5 Exhaust Gas Temperature

Figure 6 shows the exhaust gas temperature traces for different fuels. It can be seen from the figure that biodiesel fuel and its blends give lower exhaust gas temperatures than diesel fuel for all of the engine loads.

This could be because biodiesel has got lower heating value and higher number of cetane than No.2 diesel fuel. Ignition delay was occurred in fewer periods because of number of cetane increasing. In this case, sudden increase of temperature was decreased in exhaust temperatures [6].

Regarding the exhaust gas temperature, in general, there is an obvious increase with engine load. The maximum temperature is 680 °C for diesel fuel at full engine load and the minimum exhaust gas temperature 367 °C was observed at 25% engine load for pure biodiesel.

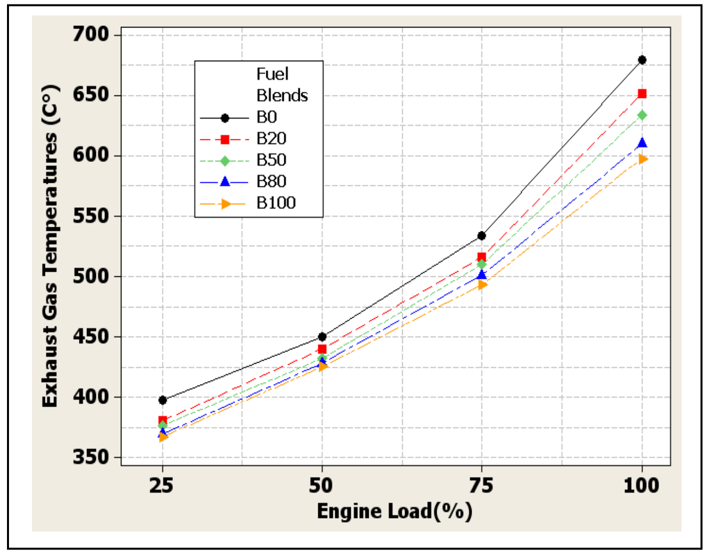

Figure 6 Effect of fuel blends on exhaust gas temperature at various engine loads (exhaust gas temperature values given are means ± 9 as standard error)

3.6 CO Emission

Figure 7 shows the CO traces for different fuels. It was observed that the CO emission decreased with the decrease in engine load. This decrease may be due to the oxygen content of the blends and pure biodiesel. Poor atomization and uneven distribution of small portions of fuel across the combustion chamber, along with a low gas temperature, may cause local oxygen deficiency and incomplete combustion [53]. The highest CO emission of 510 ppm was measured for diesel fuel at 25% engine load. Also the minimum CO emission (180 ppm) happens for B100 at full engine load. Reduced CO emissions were maintained, probably, thanks to the oxygen inherently present in the biofuel, which makes it easier to be burnt at higher temperature in the cylinder [16, 53].

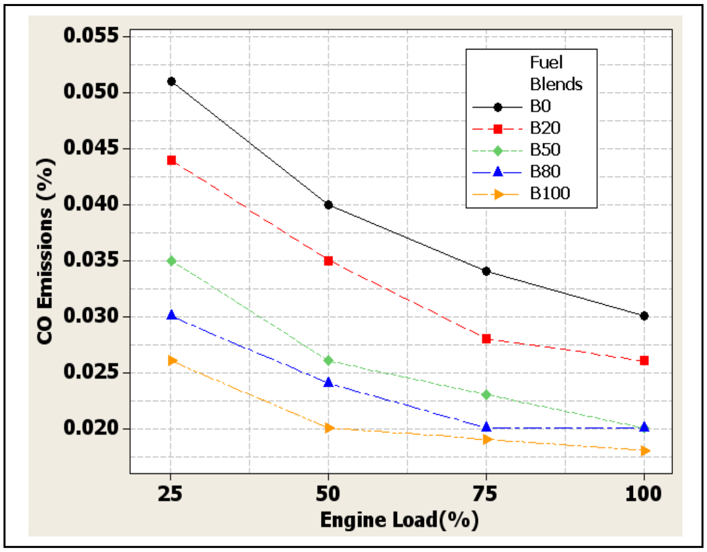

Figure 7 Effect of fuel blends on CO emission at various engine loads (CO emission values given are means ± 0.004 as standard error)

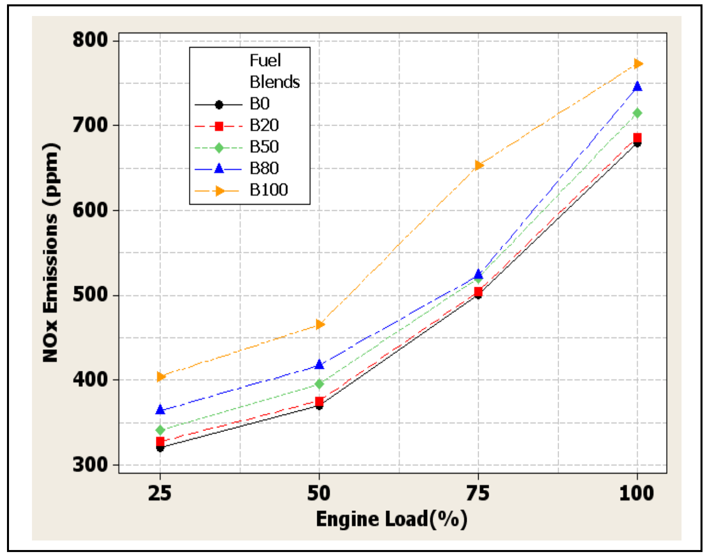

Figure 8 Effect of fuel blends on NO_x emission at various engine loads (NO_x emission values given are means ± 8 as standard error)

3.7 NOx Emission

The NO_x emissions of the engine for diesel, B20, B50, B50, B80 and B100 fuels are shown in Figure 8. It is known that NO_x formation is dependent upon volumetric efficiency, combustion duration and especially temperature arising from high activation energy needed for the reactions involved. The increase in NO_x emissions was proportional to the amount of biodiesel. In the case of pure biodiesel, the increase in NO_x emission was 24% in average compared to the diesel fuel. It has been proposed in the literature that certain injection systems suffer an unexpected advance of fuel injection timing caused by the higher bulk modulus of compressibility in the fuel blends containing biodiesel. This increases the speed of sound, causing a faster transference of the pressure wave from the injection pump to the nozzle, thereby advancing the needle lift. It is well known that advancing injection timing gives rise to an increase in NO_x emissions[54]. In addition, biodiesels contain higher oxygen component compared to diesel fuel. So it is evident that there is higher oxygen content to react with the nitrogen component in the surrounding air, resulting in a larger amount of NO_x formation [53].

The NO_x emissions of the five fuels continuously increased with the engine load. Since the reactions forming NO_x are highly temperature dependent, so the NO_x emissions have a close relation with the engine load [55].

4.0 CONCLUSION

Performance and emissions of a diesel power generator consisting of a diesel engine fuelled with waste cooking oil was experimentally investigated. Engine tests were done for biodiesel and its 0%, 20%, 50% and 80% blends with diesel fuel. The test results indicated that the lower concentration blends in terms of performance and environmentally friendly emissions (particularly for B20 and B50) could be recognized as the potential candidates to be certificated for full scale usage in unmodified diesel engines. B20 gives the best brake thermal efficiency of engine. Exhaust gas temperatures of biodiesel is decreased on average 8.2% than diesel fuel.

Also, the CO emissions decreased in average 46% with biodiesel usage but at the same time, it should be noted that higher NO_x formation occurred in biodiesel use. Therefore, research is needed to propose NO_x reduction strategies for biodiesel combustion. An increase in engine load appeared to cause an increase in brake power, brake torque, thermal efficiency, exhaust gas temperature and the emission of NO_x and a decrease in brake-specific fuel consumption and CO emission.

However, further research and development on the additional fuel property measures, long-term run and wear analysis of biodiesel-fuelled engine is also necessary along with injection timing and duration for better combustion of biodiesel in diesel power generators. Result of performance and emission tested in short periods of waste cooking oil methyl ester's performance and emission values are optimistic. However, long period tests must be done for determination of biodiesel's effect on fuel store, fuel systems' elements, engine oil and wear, injectors and burning combustion, pistons, manifolds and valves.

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