PERFORMANCE AND EMISSION COMPARATIVE ANALYSIS OF AN ENGINE OPERATING WITH TWO PALM OIL METHYL ESTERS AND THEIR BLENDS WITH DIESEL

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Abstract. *In this work we analyzed the performance and exhaust gas emissions of a single cylinder diesel engine operating with different fuels through a comparative analysis of their physical properties. The fuels utilized in these tests were: commercial diesel, palm oil methyl esters obtained by transesterification and esterification processes, and their blends with commercial diesel. The physical properties evaluated were: density, kinematic viscosity, low heating value, cetane number and percentage of carbon, hydrogen, nitrogen and sulfur.*

Keywords*: palm oil biodiesel, exhaust gas emission, engine performance*

1. INTRODUCTION

Biodiesel is defined as the mono-alkyl ester of long chain fatty acids derived from vegetable oil or animal fats (Rand, 2003; Sorensen et al., 2008). It can be classified as a combustible highly viscous liquid consisting of alkyl esters of fatty acids derived from vegetable oil or cooking grease (Gibilisco, 2006). It is also described as fatty acid methyl esters prepared from any kind of biological feedstock including vegetable oil, animal fat, single cells oil and waste material (Stevens and Verhé, 2004). According to the American Society for Testing and Materials (ASTM) Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels, biodiesel is defined as a mono alkyl ester of long chain fatty acids derived from vegetable oils or animal fats, for use in compression-ignition diesel engines (ASTM D6751-07b).

The mixture of biodiesel and petroleum diesel fuel, referred to as a biodiesel blend, is designated as BX where X is the percentage of biodiesel. For example: B20 is a blend with 20% of biodiesel and 80% of diesel fuel, B100 is 100% biodiesel and B0 is 0% biodiesel (Rand, 2003; Sorensen et al., 2008).

Biodiesel and petroleum diesel have similar properties. Hence, nearly all conventional diesel engines are able to run on any blend from pure diesel up to B20 (Pahl and McKibben, 2008). Compared to conventional diesel fuel, biodiesel has some clear disadvantages, such as higher viscosity and lower energy content. Engines running on it produce higher nitrogen oxide (NOx) emissions and have slightly reduced performance, torque, power and fuel efficiency (Demirbas, 2008; Gibilisco, 2006).

Biodiesel also has some important advantages when compared to diesel fuel. It contains almost no sulfur and is biodegradable, nontoxic and a natural lubricant. Added to diesel, it increases the capacity for lubrication of the blend, which reduces friction between engine parts and protects them against premature wear or breakdown. It has a higher flashpoint as well, about 130ºC (266ºF), so it doesn't explode spontaneously or ignite under ambient conditions. This property makes biodiesel much safer to transport and store. Although biodiesel contains 10% less energy per gallon than conventional diesel fuel, it exhibits almost the same performance compared to diesel fuel. This occurs because the reduced useable energy is offset by an approximate 7% increase in combustion efficiency. The energy balance ratio of biodiesel is nearly three times higher than that of petroleum diesel (Tickell et al., 2006; Pahl and McKibben, 2008). This property compares the energy required to grow or extract, process and distribute a fuel to the energy stored in it. Biodiesel has other advantages compared to conventional diesel fuel, such as: ready availability, renewability, higher cetane number, cloud point and cold filter plugging point (Demirbas, 2008; Kemp, 2005; Faiz, 1996). Since biodiesel comes from a renewable energy source and has lower emission levels, its production and use as a replacement for fossil fuel provides three main benefits: reduces economic dependence on petroleum oil, decreases gas emissions that cause the greenhouse effect and has a smaller contribution to the proliferation of deceases caused by the pollution of the environment (Demirbas, 2009; Gibilisco, 2006; Gevorkian, 2006).

An analysis of the exhaust gas emission in diesel engines fueled with biodiesel, extracted from several researches, showed similar results: about 85 % have found NOx increases, 10 % have obtained the same level of NOx emissions and about 5% have showed some decrease in NOx emission. Emissions of CO, total hydrocarbon (THC) and particulate matter (PM) were more homogeneous: more than 90% presented a decrease and 1 to 3% showed an increase in emissions (Lapuerta, 2008). Although these results revealed a slight increase in the emission of nitrogen oxides (NOx), replacing conventional diesel fuel by biodiesel promotes a reduction in other components present in exhaust gas emissions as well, such as carbon dioxide (CO_2) and sulfur dioxide (SO_2), which is one of the major components responsible for acid precipitation.

The following paragraphs show relevant results reported in the literature from studies conducted on the performance and exhaust gas emission of compression ignition engines, fueled with diesel fuel, pure biodiesel (B100) and its blends with diesel fuel, named previously as BX.

Zheng et al. (2008) conducted experiments in a naturally-aspirated four-stroke single-cylinder DI diesel engine coupled to a DC motoring dynamometer. The engine was modified to include exhaust gas recirculation (EGR), sequential port-injection and intake air pre-heating. Test compared an ultra-low sulphur diesel fuel with three categories of biodiesel (B100): soy, canola and yellow grease. Results showed that, without EGR and with a fixed start of injection (SOI), the biodiesel with cetane number (CN) similar to diesel fuel produced greater NOx emissions. Meanwhile, the biodiesel with CN greater than that of diesel produced similar NOx emissions. The soot, CO and THC emissions were generally lower for biodiesel. It was observed for all fuels tested that, with the diesel engine operating at steady-state conditions, NO_X decreased as EGR increased. It was also observed that soot increased with increasing EGR until the ignition delay (τ_{ID}) was prolonged by 50–70%. After this point, a reverse trend was observed with further ignition delay.

Almeida et al. (2002) studied performance and exhaust gas emissions of a naturally aspirated MWM 229 direct injection four-stroke, 70 kW diesel-generator, fuelled with preheated palm oil and diesel fuel. Their tests showed that, when the engine was operating with palm oil, exhaust temperature increased with load and specific fuel consumption was almost 10% higher at low loads. It was also observed for both fuels that CO emissions increased with load. Tests also showed that: the HC emissions of both fuels were low (up to 75% of the load) but tended to increase at higher loads and NO_X emissions increased as load increased. Furthermore, NO_X emissions were lower when the engine was fueled with palm oil, the levels of CO_2 and O_2 emissions were almost the same for both fuels and the lowest CO emissions were obtained with diesel.

Rakopoulos et al. (2006) conducted tests using diesel fuel and biodiesel as well as vegetable oil blends with 10 and 20% added to diesel. The biodiesel fuels utilized were: cottonseed oil methyl ester, soybean oil methyl ester, sunflower oil methyl ester, rapeseed oil methyl ester and palm oil methyl ester. The vegetables oils utilized were: cottonseed oil, soybean oil, sunflower oil, corn oil and olive kernel oil. Performance and exhaust gas emissions of a naturally aspirated DI diesel engine coupled to an electric DC dynamometer were analyzed. This engine operated at an angular velocity of 2000 rpm at medium and high loads. Results showed that biodiesel blends emitted the lowest levels of soot and CO emissions, followed by conventional diesel fuel and vegetable oil blends. Compared to conventional diesel fuel, NO_X emitted by all biodiesel and vegetable oil blends were slightly lower. It was also noted that NO_X emissions decreased with an increase in the percentage of the biodiesel or vegetable in the diesel. All vegetable oil blends presented an increase in HC emissions compared to conventional diesel fuel. An increase was also observed for engines operating at medium load case with all biodiesel blends, but there was no definite trend at high loads. For high load case, all biodiesel and vegetable oil blends presented higher specific fuel consumption than pure diesel.

The objective of the present study is to compare the performance and exhaust gas emissions of a single cylinder diesel AGRALE M95 through a physical property analysis of the different fuels utilized. The chosen fuels are: commercial diesel, palm oil biodiesel (B100) obtained by esterification and transesterification processes, and their blends (B20) and (B50) with commercial diesel. The physical properties considered are: density, kinematic viscosity, low heating value, cetane number and the percentage of carbon, hydrogen, nitrogen and sulfur.

2. MATERIAL AND METHOD

2.1 Commercial Diesel

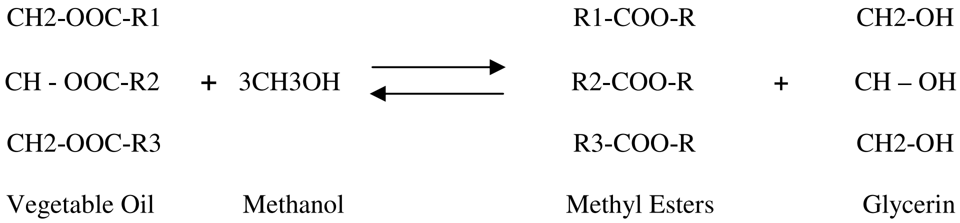
The diesel used in all tests reported from this point on is a standard Brazilian commercial fuel. This means that CNPE (National Energy Policy Council) established through Resolution N° 2 from March 13th 2008, starting July 1st 2008, 3% as the minimum biodiesel percentage to be added to commercial diesel fuel. Both B20 and B50 blends have been produced considering 3% of biodiesel already mixed with diesel.

2.2. Palm oil production process and specifications

2.2.1 Transesterification and esterification

On a chemical level, biodiesel is a fatty acid methyl or ethyl ester. It is produced out of triacylglycerol (triglycerides) via transesterification in the former case and out of fatty acids via esterification in the latter case.

Transesterification (alcoholysis) is a reversible reaction process in which one ester is converted into another by an interchange of ester groups. One mole of triglyceride oils, contained in vegetable oils, animal fats or recycled greases, reacts with three moles of alcohol to form one mole of glycerol (glycerin) and three moles of the fatty acid alkyl ester (biodiesel). In order to shift the equilibrium to the right, an alcohol is added in excess over the stoichiometric amount. Methanol is typically employed but ethanol can also be used. The two main products, glycerol and fatty acid methyl / ethyl esters (FAME/FAEE), are not miscible and thus form separated phases: an upper ester phase and a lower glycerol phase. It is important to note that Glycerin is used in many household products, such as: cosmetics, plastics, lubricants and antifreeze. A typical model of the transesterification chemical reaction is shown in figure 1 (Tickell, J et al., 2006; Soetaert and Vandamme, 2009; Kader and Delseny, 2002).



$$\begin{array}{llllllll}
CH2\text{-}OOC\text{-}R1 & & & & R1\text{-}COO\text{-}R & & CH2\text{-}OH \\
CH\text{ - }OOC\text{-}R2 & + & 3CH3OH & \rightleftarrows & R2\text{-}COO\text{-}R & + & CH - OH \\
CH2\text{-}OOC\text{-}R3 & & & & R3\text{-}COO\text{-}R & & CH2\text{-}OH \\
\text{Vegetable Oil} & & \text{Methanol} & & \text{Methyl Esters} & & \text{Glycerin}
\end{array}$$

Figure 1. Representation of transesterification chemical reaction

Esterification is the process in which a fatty acid reacts with a mono-alcohol to form an ester. This reaction is typically in equilibrium as well. Hence, in order to increase the yield of fatty acid alkyl esters, it is necessary to use an excess of alcohol or to remove one of the end products so that the reaction equilibrium is shifted to the right. A typical model of the esterification chemical reaction is shown in figure 2.

$$R1COOH + CH3OH \xrightarrow{H+} R1COOCH3 + H2O$$

$$R1COOH + C2H5OH \xrightarrow{H+} R1COOC2H5 + H2O$$

Figure 2. Representation of esterification chemical reaction

Either transesterification or esterification reaction requires heat and a strong base catalyst in order to increase reaction rates (Soetaert and Vandamme, 2009; Kader and Delseny, 2002). Common choices for catalysts are sodium hydroxide (NaOH), also known as “caustic soda”, and potassium hydroxide (KOH).

2.2.2 Palm Oil Biodiesel

Palm (Elaeis guineensis) is an African plant suitable for tropical regions due to their hot and humid climate as well as high and well distributed precipitation throughout the year. It is able to produce about three to six tons of oil per hectare per year. Moreover, it has the advantage of being a perennial culture. This means no time is wasted between harvests and fruits are produced during the entire year (Ellstrand and Norman, 2005).

The African palm produces two types of oil: palm oil and palm oil kernel. The former is extracted from the fruit’s fleshy part and the latter is derived from the fruit kernel. Palm oil represents 10% of the raw material used to manufacture biodiesel in the world (Pahl and McKibben, 2008).

In this work, the palm oil biodiesel utilized comes from two different production processes: esterification, called Palmdiesel (PO-E), and transesterification, called palm oil biodiesel (PO-T).

Palmdiesel was produced from the residue of a distillation process applied to the fleshy part of the palm fruit. The result of a partnership between UFRJ (Federal University of Rio de Janeiro) and Agropalma S/A, it was patented by UFRJ and Agropalma holds the exclusive right of production. This process to produce biodiesel does not generate glycerin or soap. It is feasible because a heterogeneous catalyst was utilized instead of KOH and NaOH. Palmdiesel has higher cetane index compared to all other types of biodiesel derived from vegetable oils. Its oxidative stability is four times higher than biodiesel from soybean and it also has higher lubricity than diesel.

Palm oil biodiesel was produced by in Chemistry Departament of Military Institute of Engineering.

2.3. Fuel Properties

Cetane numbers of all the fuels employed in this work were obtained using the ASTM D613-01standard. Procedures for obtaining the number of cetane were performed in the Thermal Engines Laboratory of COPPE/UFRJ, using a single cylinder, four stroke cycle, variable compression, indirect injected diesel engine (CFR). The acid test was performed in the Department of Chemistry of the Military Institute of Engineering (IME). Physical properties characteristics of such fuel are reported in Table 1.

Table1. Fuel specifications of commercial diesel, PO-E, PO-T and their blends with commercial diesel

PROPERTY	**RESULT**							**METHOD**
	CD*	**B20-E**	**B50-E**	**B100-E**	**B20-T**	**B50-T**	**B100-T**	
Density	842.7	847.8	856.3	871.9	842.8	857.0	872.1	ASTM D 4052
Kinemact Viscosity	3.294	3.644	3.830	4.381	3.583	3.982	4.727	ASTM D 445
Sulfur (%)	412.23	340.63	226.24	6.48	443	243	3.13	ASTM D 5453
Carbon (%)	85.84	83.80	81.45	76.98	85.73	80.48	75.47	ASTM D 5291
Hydrogen (%)	13.54	13.80	13.52	13.13	13.81	13.18	12.69	ASTM D 5291
Nitrogen (%)	0.09	0.04	0.07	0.07	0.10	0.09	0.07	ASTM D 5291
Low heating value	10068	9819	9448.5	8784	10125	9405	8802	ASTM D 4809
Cetane Number	48.8	49.7	56.1	59.3	52.1	54.4	60.3	ASTM D 613-01
Acid Number	-	-	-	1.5	-	-	0.5	-

CD* Commercial Diesel

2.4 Engine and Instrumentation

2.4.1 Engine and Dynamometer

Tables 2 and 3 show the operational parameters of the engine and dynamometer used at Thermal Engines Laboratory of COPPE/UFRJ, respectively.

Table 2. Diesel engine specifications

ENGINE	**AGRALE**
Model	M95
Type	Water-cooled, 4 stroke
Dimension (L × W × H)	683 × 575 × 702 (mm)
Number of cylinders	1
Cylinder volume	0.744 dm^3
Compression ratio	21.0:1
Bore × Stroke	95 × 105 mm
Valves per cylinder	2
Maximum torque NBR ISO 1585	4.2 mdaN at 2500 rpm
Baterry	12 V / 45 Ah
Injection system	Direct injection
Rated Power NBR ISO 1585	12.9 kW at 3000 rpm 11.4 kW at 2600 rpm
Injection crank angle	-17 º

Figure 2 shows a schematic representation of the equipments used in this work. The induction dynamometer is coupled to the engine through a load cell for torque measurements. An operator specifies engine speed and load using an automated control / data acquisition system.

Table 3 - Dinamometer Specification

DINAMOMETER	**DYNAM**
Model	66 DG
Serial Number	00279-1
Capacity	30 HP at 2700 rpm to 8000 rpm
Water Requirements	3 GPM 35 Psi (min) 100 Psi (max)
DC Excitation	45.0 V 2.0 A 17 Ω at 20 ºC

2.4.2 Precision Balance

Engine fuel utilization was monitored during tests with a high precision balance located next to the fuel tank. Fuel consumption was calculated using a data acquisition computer program coupled to the balance and fed every second. Consumption data measurements started after engine stabilization and were averaged over one minute. The technical specifications of this precision balance are reported in Table 4.

Table 4 - Balance Specification

BALANCE	OHAUS
Model	ARD110
Measurement weights (g) :	4.1 kg
Weighing instruments type	Inox weighing tray Counting
Accuracy (g)	100 mg
Tray dimension (mm)	Diam. 18 cm
Stabilization time (s)	3 s
Dimension (HxWxD) (mm) :	110x217x343 mm

2.4.3 Gas Analyzer

The gas analyzer MODAL 2010-AO from NAPRO, whose technical specifications are reported in Table 5, measures the concentration of CO, CO_2 and O_2 in volumetric percentage (v%) and the concentration of HC and NOx in parts per million (ppm). This equipment uses a non-dispersive infrared system to measure for the former and electro-chemical cells to measure the latter. Furthermore, it is also capable of quantifying the angular speed and temperature of the engine lubricating oil. A compressor cleans the line that feeds exhaust gases to the gas analyzer.

Table 5 - Gas Analyser MODAL 2010-AO specification

TYPE	RESOLUTION	ACCURACY	GRADE
HC	1 ppm	12 ppm or 5% of the reading$^{(1)}$	0 - 2000 ppm
CO_2	0.01%	0.06% or 5% of the reading$^{(1)}$	0 - 20 %
CO	0.1%	0.5% or 5% of the reading$^{(1)}$	0 - 15 %
O_2	0.01%	0.1% or 5% of the reading $^{(1)}$	0 - 25 %
NOx	1 ppm	32 ppm in the range from de 0 to 1000 ppm 60 ppm in the range from 1001 to 2000 ppm 120 ppm in the range from 2001 to 5000 ppm	0 - 5000 ppm

$^{(1)}$ The greatest value

2.5 Test Procedure

2.5.1 Experimental Setup

All experiments were performed at sea level, with an average temperature of approximately 300 K, relative humidity of 70% and pressure of 762 mm/Hg. The test area was divided into two separated parts: control and equipment sections. The former contains the engine´s ignition system and three computers, each one connected to a different device: dynamometer, gas analyzer and balance. The latter contains the dynamometer, water tank, compressor, precision balance and all other instruments described in Figure 2.

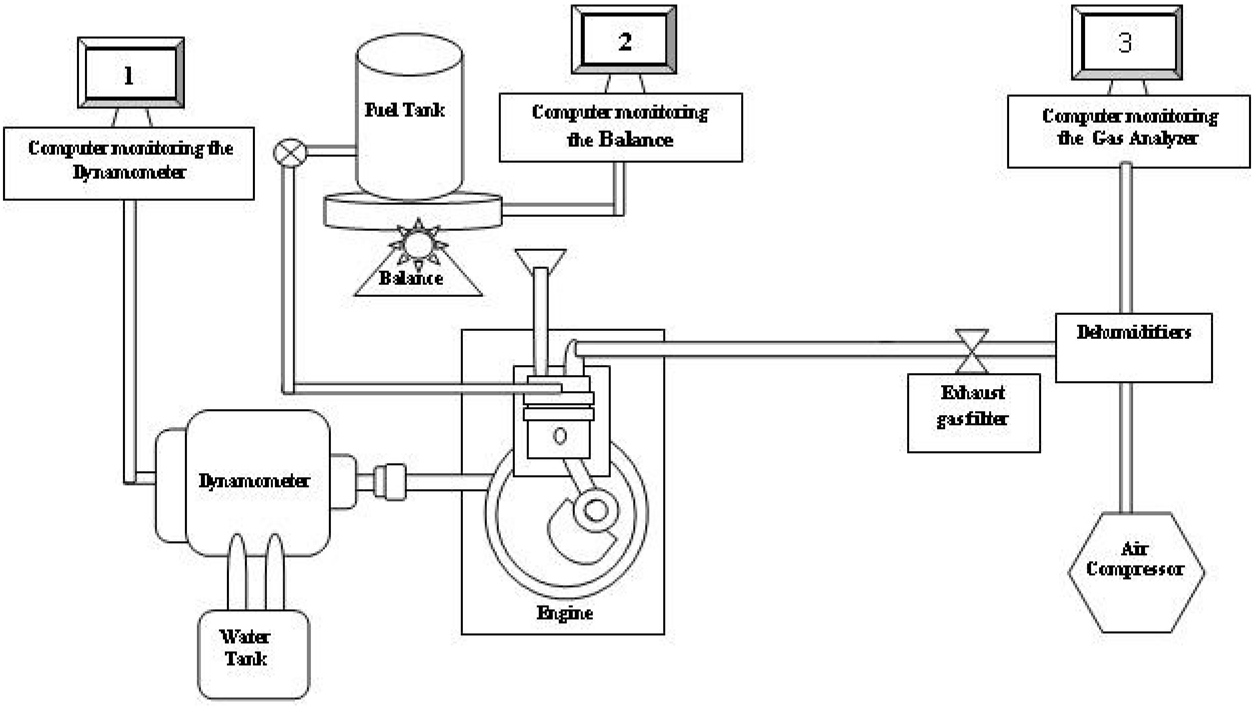


Figure 2. A schematic representation of the mechanism utilized to carry out the present experiments

2.5.2 Preliminary Measurements

A few procedures were adopted for each test so as to guarantee result consistency:

i) Same ambient conditions, verified through temperature, pressure and relative air humidity.

ii) Engine ran at idle for five minutes before each experiment in order to stabilize engine cooling water and lubricating oil temperature.

2.5.3 Preventive Measures

iii) Tests were interrupted and data discarded whenever results did not achieve steady-state.

iv) When exchanging fuels, the engine ran for five minutes on diesel without data acquisition to remove any residue of the previous fuel utilized.

2.5.4 Performance and Emission Test Procedures

Performance and exhaust gas emission analysis were performed using the instruments specified in section 2.3 and illustrated in figure 2. After going through the preliminary measures described in section 2.5.2, all tests followed the following script:

i) Load and angular velocity were set by computer 1 through the software DinMon developed by Logs Sistemas Eletrônicos Ltda. It then provided torque and power data, which were stored on this computer.

ii) Specific consumption was measured by the Balance OHAUS ARD110, stored and processed by computer 2.

iii) The emissions levels of CO, CO_2, HC, O_2 and NOx produced by the engine were captured by the Gas Analyzer NAPRO MODAL 2010-AO. Each emission data was sent to computer 3 for storing and processing.

3. RESULTS AND DISCUSSION

All graphics showed in section 3 correspond to the results obtained with a CI engine AGRALE M95 fueled with commercial diesel, palm oil biodiesel (B100) obtained by transesterification and esterification processes and their blends B20 and B50 with commercial diesel. The experiment was conducted with this engine operating at variable loads, as mentioned in section 2.5. The label Diesel* mentioned in all figures corresponds to commercial diesel, whose properties were described in section 2.3.

3.1 Specific Fuel Consumption

Specific consumption is defined as the fuel mass flow rate per unit of power produced (Johnston, 1992). It was observed in the present study that specific fuel consumption of palm oil biodiesel and is blends were slightly higher than that for commercial diesel, in agreement with Lapuerta (2008), as is shown in Figure 3.

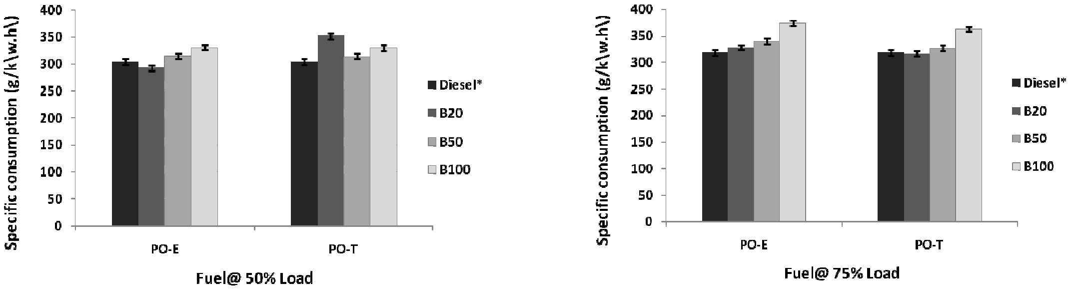


Figure 3. Specific Fuel Consumption with the engine operating at 50% and 75% of full load

When the engine was operating at 50% of the full load, the specific consumption of PO-E and its blends increased about 4% compared to its commercial diesel counterpart. This value went up to 7% at 75% of the full load. The average specific consumption of palm oil biodiesel (B100), compared to commercial diesel, was 7% higher on 50% of full load and 10% higher on 75% of full load. Specific fuel consumption of PO-E and its blends were lower than their respective PO-T counterparts as shown in Figure 4.

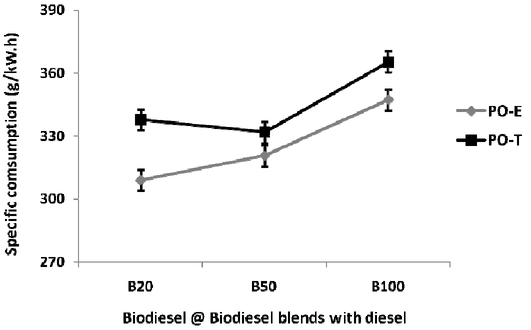


Figure 4. Specific Fuel Consumption with the engine operating with PO-E and PO-T

Specific consumption is directly related to the heat value of a fuel. Higher heat values of fuel lead to lower specific fuel consumptions for a given load. As expected, both types of biodiesel and their blends with commercial diesel showed higher specific fuel consumptions because of their lower heat values. Furthermore, this increase is proportional to the percentage of biodiesel present in each blend.

3.2 CO_2 Emissions

Adequate quantities of air and fuel, combined with a complete combustion, would result in carbon dioxide (CO_2), nitrogen (N_2) and water (H_2O). However, complete combustion is generally impracticable to achieve unless the reaction takes place under controlled situations, such as in a laboratory. Therefore, it is necessary to provide the correct air/fuel ratio to reduce CO_2 emissions. This is necessary because, even though CO_2 is not directly damaging to humans, it is harmful to environment and also contributes to global warming (Hillier, and Coombes, 2004). Available literature (Tickell, 2000; Tickell, 2006; Feigon, 2003) shows a considerable reduction in CO_2 emissions when the engine is fueled with biodiesel. Our tests indicate that these reductions are moderate at smaller loads but more significant at higher loads, as shown in Figure 5. Furthermore, the use of PO-T promotes significantly less CO_2 emissions when compared to either PO-E. However, this is true only when small amounts of PO-T are added to commercial diesel.

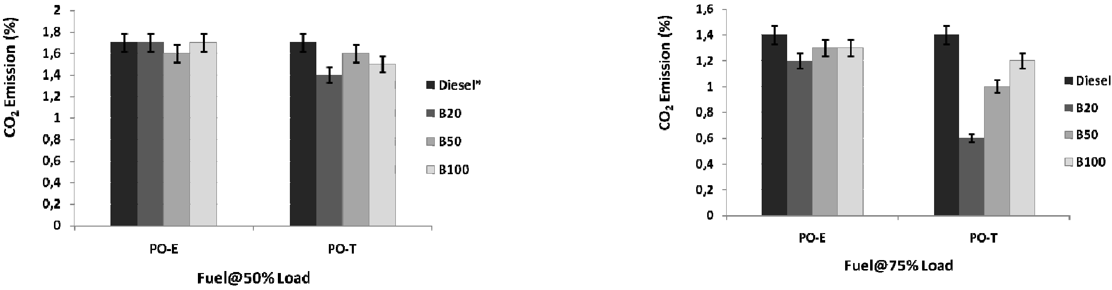


Figure 5. CO_2 Emission (%) concentration with the engine operating at 50%and 75% of full load

3.3 NOx Emissions

NOx emissions are generated when nitrogen is burned or oxidized. Since air is composed by 78% nitrogen, any engine will produce some level of NOx regardless of which fuel it uses. Created due to high temperature levels with ample local supply of oxygen, NOx found in the exhaust gases of diesel engines is produced within lean flame regions. In these cases, it is formed by either micro volume combustion or independent flame propagation (Gruden, 2003; Sengupta, 1989; Tickell, 2000; Faiz, 1996b).

Our results showed that NOx emissions from biodiesel and its blends are higher when compared to commercial diesel, as shown in Figure 6, in agreement with most results found in the literature (Lapuerta, 2008).

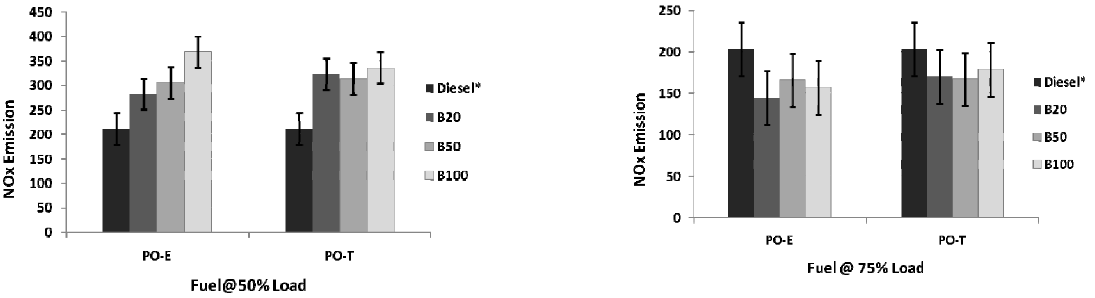


Figure 6. NOx concentration (ppm) with the engine operating at 50% and 75% of full load

3.4 Cetane number

Cetane number is a measurement of the ignition delay in compression ignition engines. It is defined as the time period between injection and combustion (ignition) of the fuel. Figure 7 shows the effect of PO-E and PO-T fuel cetane number on ignition delay of the engine M95 AGRALE. In this figure, the results are presented at various speeds and loads. The symbol convention is *xxx@yyy*, where *xxx* is the velocity (rpm) and *yyy* is the load (N.m). Fuels with higher cetane number, as well as engines operating at higher RPM and/or higher loads, will lead to shorter ignition delay periods than otherwise. This relation is true for any combination of these three parameters. This information can be a tool to improve biodiesel efficiency.

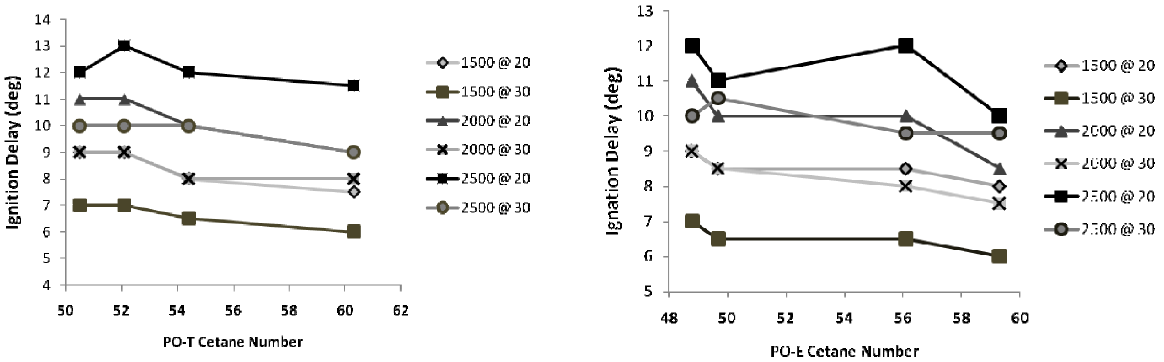


Figure 7. Effect of fuel cetane number on ignition delay in the M95 AGRALE engine operating at 50% and 75% of full load at various speeds

4. ACKNOWLEDGEMENTS

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5. CONCLUSIONS

As we can find in the literature available, the specific fuel consumption of palm oil biodiesel, compared with commercial diesel fuel showed an increase of almost 10%, for both percentage of loads (50% and 75%). It was also observed that blends of biodiesel with commercial diesel produced by esterification process have lower specific fuel consumption than the biodiesel produce by transesterification process.

Both biodiesel fuels as their blends showed lower CO_2 emissions than the commercial diesel. Tests demonstrated that CO_2 emissions increased as the amount of biodiesel in the blend increases.

When the engine was operating with both biodiesel fuel at 50% of load, NOx emissions present similar results with the literature available. However, at 75% load, there was a reduction of NOx compared with commercial diesel. This reduction was more pronounced for biodiesel produced by esterification process.

Results show that fuels with higher cetane number will have shorter ignition delay periods than lower cetane fuels even if the angular speed and the load of the engine vary.

During the tests, it was difficult to obtain data on the engine operating with angular speed of 1500 rpm and torque of 30 Nm. In this situation, the engine has considerable instability regardless of the fuel used.

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