ANALYSIS OF EXHAUST EMISSIONS IN A STATIONARY DIESEL ENGINE OPERATING WITH DIESEL / BIODIESEL BLENDS

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Abstract. *In this work we analyzed the environmental impact of the AGRALE M95 single cylinder diesel engine operating with diesel / biodiesel blends. This is achieved by measuring the levels of NO_X, CO, CO_2 and particulate matter in the exhaust emissions. The biodiesel used in this work was extracted from palm oil through an esterification process. Oil palm is a plant commonly found in Brazil and is a viable candidate for the Brazilian Government's plan to increase the amount of biofuel used in commercial diesel blends. Blends ranging from current commercial diesel (B3) to pure vegetal oil (B100) were analyzed. Each one was characterized through its physical properties, such as: density, kinematic viscosity, low heating value, cetane number and percentages of carbon, hydrogen, nitrogen and sulfur.*

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

1. INTRODUCTION

Biodiesel is defined as a mono-alkyl ester of long-chain fatty acids derived from renewable biolipids (Demirbas, 2008). It is also described as a fatty acid methyl ester 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 utilized in compression-ignition diesel engines (ASTM D6751-07b).

Biodiesel and petroleum diesel have very similar properties. Hence, it can be either mixed with or used as a substitute for its fossil fuel counterpart. This led to a significant increase in the number of studies related to performance and exhaust gas emissions of a compression-ignition (CI) diesel engine fueled with biodiesel over the past few years. Although test results revealed a slight increase in the emission of nitrogen oxides (NO_X), the replacement of conventional diesel fuel by biodiesel promotes the reduction in other components present in exhaust gas emissions, such as: carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM).

Biodiesel has other advantages compared to conventional diesel fuel, such as: portability, ready availability, renewability, biodegradability, lower sulfur content, higher centane number, flash point, cloud point and cold filter plugging point (Faiz and Michael, 1996a; Kemp, 2005; Demirbas, 2008). The production and use of biodiesel as a replacement for fossil fuels provides three main benefits: reduces economic dependence on petroleum oil, decreases gas emissions that cause the greenhouse effect and diminishes the proliferation of diseases caused by environmental pollution (Demirbas, 2009). Biodiesel also has other disadvantages compared to conventional diesel fuel: higher viscosity, lower energy content, higher nitrogen oxide (NOx) emissions and lower engine power (Demirbas, 2008).

Nevertheless, these conclusions must be approached with care. There are noticeable differences amongst many studies reporting biodiesel emissions and performance. They are usually due to the use of engines with different technical characteristics as well as biodiesel produced from different raw material.

Despite these issues, an analysis of the exhaust gas emission from diesel engines fueled with biodiesel, extracted from several researches, does show similar trends. NO_X emissions increased in about 85%, remained approximately the same in 10% and decreased in the remaining 5% of these studies. On the other hand, CO, total hydrocarbon (THC) and PM test results were slightly more homogeneous. More than 90% reported a decrease, with only about 1 to 3% showing an increase, in their respective emissions (Lapuerta *et al*, 2008).

The following paragraphs show relevant results from studies conducted on the performance and exhaust gas emission of compression engines, fueled with pure diesel (B0), pure biodiesel (B100) and also its blends with diesel fuel (BX) reported in the literature.

Wang *et al* (2000) used B35 in two different engines: a 1980s model Cummins 855 and a 1990s DDC series 60. They measured an increase in NOx in the first one and a small average decrease in the last model engine. The decrease in NO_X was considered an exception by them.

Peterson and Reece (1996) conducted tests in two pickup trucks, with 5.9 L turbocharged and intercooled direct injection diesel engines. Initial tests conducted in 1994 compared exhausts gases from three different fuels: rapeseed methyl ester (RME), rapeseed ethyl ester (REE) and blends of biodiesel with low sulfur diesel. Results showed that REE reduced HC (8.7%), CO (4.3%) and NOx (3.4%) emissions compared to RME. It was also noted that emissions from REE and RME compared to emissions from diesel resulted, on average, in reductions of HC (52.4%), CO (47.6%), NOx (10.0%) and increase of CO_2 (0.9%) and PM (9.9%). Later tests conducted in 1995 were performed with and without a catalytic converter installed on the vehicles. Their purpose was to also compare exhausts gases from four different types of fuel: low sulfur diesel reference fuel, REE, a mixture of 20% REE and 80% of diesel (B20) and a mixture of 50% REE and 50% of diesel (B50). Results showed reductions in HC (63%), CO (33%), NO_X (10%), unchanged CO_2 emissions and an increase in PM (30%) for REE, all compared to the low sulfur diesel reference fuel. The catalytic converter affected only the HC and PM emissions. It reduced HC and PM emissions by 10.5 and 45%, respectively, when compared to the low sulfur diesel reference fuel. Compared to REE, respective reductions were 13.6 and 56%.

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.

Lin and Lin (2006) used a four-cylinder, naturally aspirated, direct-injection diesel engine, to study four different fuels: biodiesel with additional peroxidation process (C1), biodiesel without additional peroxidation process (C2), a commercial biodiesel and ASTM No. 2D diesel. Their results showed that higher engine speeds increase brake thermal efficiency fuel consumption rate, equivalence ratio and exhaust gas temperature but decrease brake specific fuel consumption (BSFC) and emissions of CO_2, CO and NO_X. Compared to ASTM No. 2D diesel, the others three fuels exhibited lower emission levels of CO and CO_2, lower exhaust gas temperature, higher fuel consumption rate and higher brake thermal efficiency. Results showed higher fuel consumption rate and break specific fuel consumption (BSFC) in biodiesel C1, compared to biodiesel C2. However, brake thermal efficiency, equivalence ratio and emission levels of CO_2, CO and NO were found to be lower in biodiesel C1 compared to biodiesel C2. Among all the four fuels tested, biodiesel C1 presented the lowest equivalence ratio and emission levels of CO_2, CO and NO.

Dorado *et al* (2003) tested, under several steady-state operating conditions, a direct injection Perkins engine fueled with waste olive oil methyl collected from several Spanish hospital kitchens and filtered from solid impurities. Although NO_2 increased up to 81% compared to conventional diesel fuel, test results showed a significant reduction in the others emission: CO (58.9%), CO_2 (8.6%), NO (37.5%) and NO_X (32%). Results also showed a significant reduction in SO_2 (57.7%), which decreases the acid rain risk.

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.

Kalam and Masjuki (2004) studied the exhaust gas emissions and deposit characteristics of a water-cooled, four-stroke, single-cylinder, DI diesel engine. The fuels utilized were: preheated crude palm oil (CPO), its emulsions with 1% water (CPO99), 2% water (CPO98) and 3%water (CPO97) and ordinary diesel fuel (OD). For each fuel, tests ran for 100 hours at a constant speed of 2700 rpm and 5.50 Nm load. Results showed that CPO produced the lowest levels of HC and CO emissions, followed by OD, CPO99, CPO98 and CPO97. However, CPO produced the highest level of NO_X emissions followed by OD, CPO99, CPO98 and CPO97. Compared to OD fuel, CPO presented lower PM emissions and higher volatile deposit. It was found that increasing the percentage of water added to the fuel reduced NO_X emissions and volatile deposits, but also increased PM emissions.

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 an AGRALE M95 single cylinder diesel engine, fueled with commercial diesel fuel, palm oil biodiesel (B100) from two different sources and their blends (B20 and B50).

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 Nº 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. Production process and specifications for 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, 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). The palm oil biodiesel used in this study, also called Palmdiesel, was produced from the residue of palm distillation. This biodiesel was patented by UFRJ (Federal University of Rio de Janeiro), and Agropalma S/A holds the exclusive right of production. The schematic of an esterification chemical reaction is shown in Figure 1.

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

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

Figure 1. Representation of esterification chemical reaction

The process developed by UFRJ and Agropalma S/A 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. Some physicochemical properties of the fuels used in this work are reported in Table 1. Cetane numbers were obtained following the ASTM D613-01standard with a single cylinder, four stroke cycle, variable compression, indirect injected diesel engine (CFR) at the Thermal Engines Laboratory / COPPE / UFRJ. The acidity test was performed at the Catalyze Laboratory / Military Institute of Engineering (IME). All other properties were obtained at the National Institute of Technology (INT).

Table1. Fuel specifications

CHARACTERISTIC	RESULT				METHOD
	CD*	B20	B50	B100	
Specific Mass at 20 ºC (kg/m^3)	842.7	847.8	856.3	871.9	ASTM D 4052
Kinematic Viscosity at 40 ºC (mm^2/s)	3.294	3.644	3.830	4.381	ASTM D 445
Sulfur Content (% m/m)	412.23	340.63	226.24	6.48	ASTM D 5453
Carbon Content (% m/m)	85.84 ± 0.13	83.80 ± 0.20	81.45 ± 0.30	76.98 ± 0.31	ASTM D 5291
Hydrogen Content (% m/m)	13.54 ± 0.11	13.80 ± 0.01	13.52 ± 0.06	13.13 ± 0.18	ASTM D 5291

Nitrogen Content (% m/m)	0.09	0.04	0.07	0.07	ASTM D 5291
Higher Heat Value (Kcal/kg)	10765 ±23	10536 ± 1	10144.5 ± 18.5	9460.2 ± 5.0	ASTM D 4809
Lower Heat Value (Kcal/kg)	10068 ± 23	9819,6 ± 0.7	9448.5 ± 18.7	8784.0 ± 5.0	ASTM D 4809
Centane Number	48.8	19.7	56.1	59.3	ASTM D 613-01
Acidity	-	-	-	1.5	-

* Commercial Diesel

2.3 Engine and Instrumentation

2.3.1 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

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

2.3.2 Opacimeter

The INMETRO standard NIE-DIMEL-080 classifies opacimeter of partial flow as the instrument used to determine the opacity of smoke generated by a compression ignition engine.

The opacimeter NA-9000 from NAPRO, described in Table 4, was the equipment employed to monitor particulate matter present in the exhaust gases of the engine used in the present study. In addition to measuring opacity, it also performs its own calibration automatically.

Table 4 - Opacimeter Specification

OPACÍMETER	**NAPRO**
Model	NA-9000
Opacity	0 - 100%
Absorption coefficient (K)	0 – 9.99 m (-1)
Accuracy	+/- 2 %
Resolution	0.1 %
Flow	Parcial
Temperature in the chamber	75 °C nominal
Length of beam	430 mm
Response Time	0.9 – 1.1s
Operating temperature	5 - 40 °C
Operating humidity environment	0 - 95%

2.3.3 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 5.

Table 5 - 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

2.3.4 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

2.4 Test Procedure

2.4.1 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 four computers, each one connected to a different device: dynamometer, gas analyzer, opacimeter and balance. The latter contains the dynamometer, water tank, compressor, opacimeter, precision balance and all other instruments described in Figure 2.

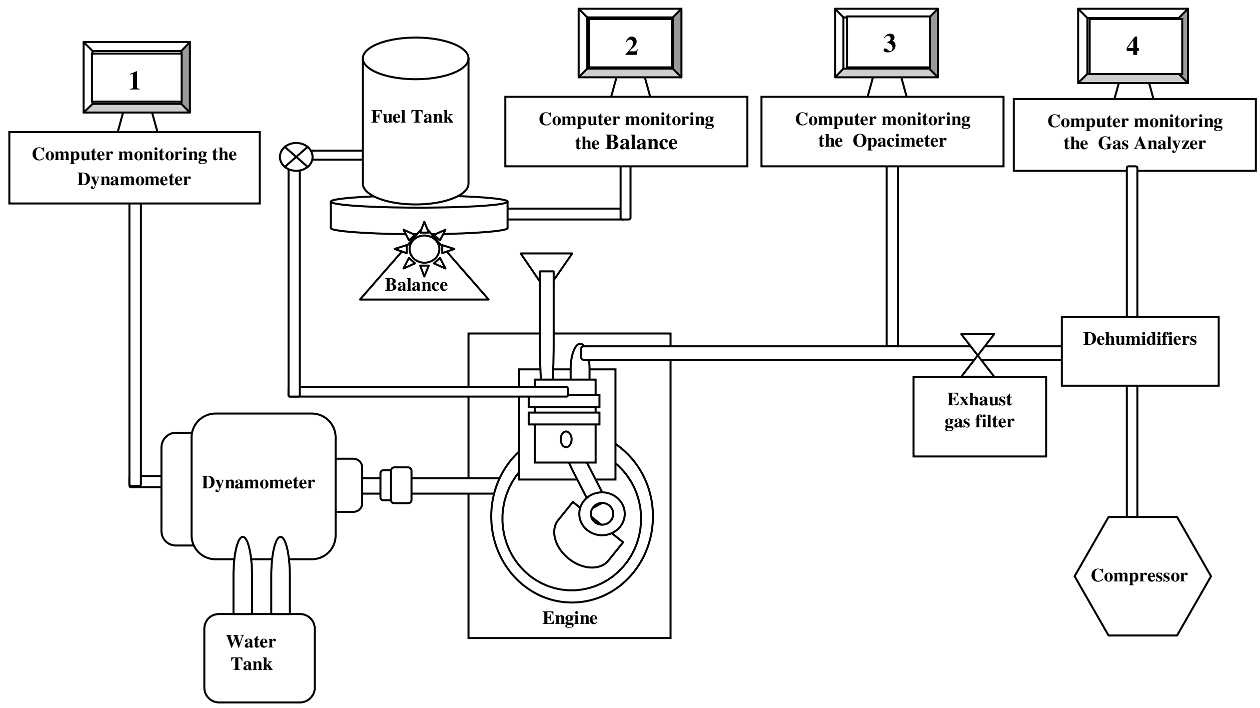


Figure 2. A schematic representation of the mechanism utilized to carry out the present experiments

2.4.2 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 temperatures.

2.4.3 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.

2.4.4 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 2.4.2, 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) Exhaust gas opacity was measured by Opacimeter NAPRO NA-9000, stored and processed by computer 3.

iv) 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 4 for storing and processing.

3. RESULTS AND DISCUSSION

All figures shown next correspond to the results obtained when following the above procedure for each of the four types of fuel utilized in the present study: commercial diesel, palm oil biodiesel (B100) and its blends with commercial diesel named B20 and B50. For each fuel, the engine was subjected to the angular velocities: 1500, 2000, 2500 rpm. Furthermore, the engine was subjected to 50, 75 and 100% of the full load for each angular velocity case. Diesel*, mentioned in these figures, corresponds to commercial diesel, whose details were described in item 2.1. 2600 rpm represents the angular velocity of this engine operating at maximum load.

3.1 Specific Fuel Consumption

Specific consumption is defined as the fuel mass flow rate per unit of power produced (Johnston *et al*, 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 *et al* (2008), as is shown in Figure 3.

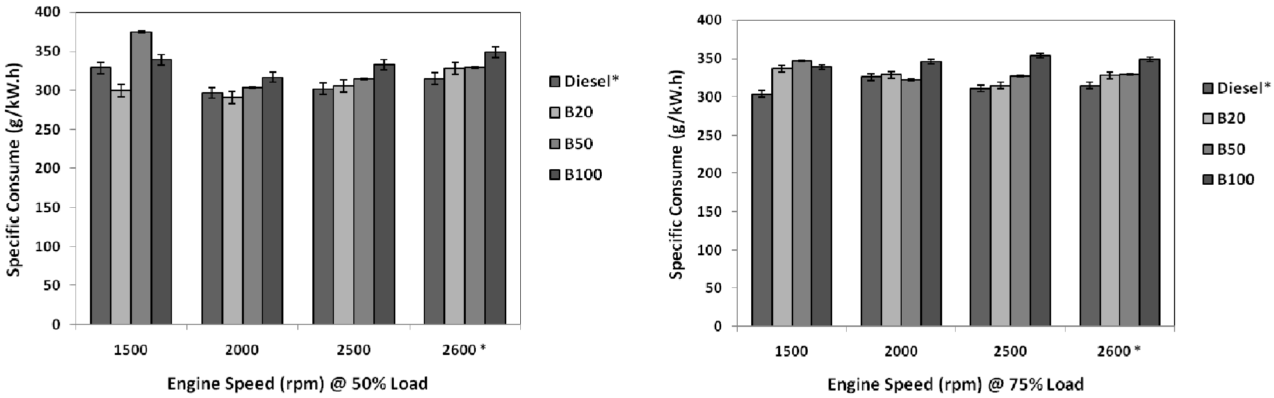


Figure 3. Specific fuel consumption with the engine operating at 50% and 75% of full load at various speeds

When the engine was operating at 50% of the full load, the specific consumption of biodiesel 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.

In the tests, the engine presents an increasing of specific fuel consumption operating with biodiesel and biodiesel blends because, compared with diesel commercial, biodiesel and its blends have lower heat value. Therefore, to compensate the lower amount of energy per mass of fuel, biodiesel and its blends require more fuel to keep the power of engine operating at constant loads.

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). But even thought this reaction cannot be achieved, the combustion of air and fuel will always product carbon dioxide (Hillier and Coombes, 2004).

Figure 4 shows that CO_2 emissions from fuels B20, B50 and B100 whose levels varied between 1.8 and 3.2%, while commercial diesel fuel had the lowest CO_2 emission rates, below 2.1%.

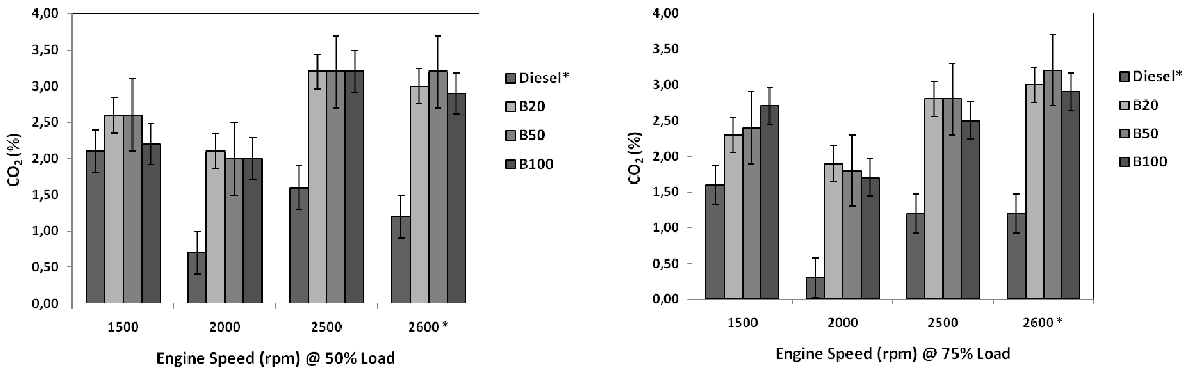
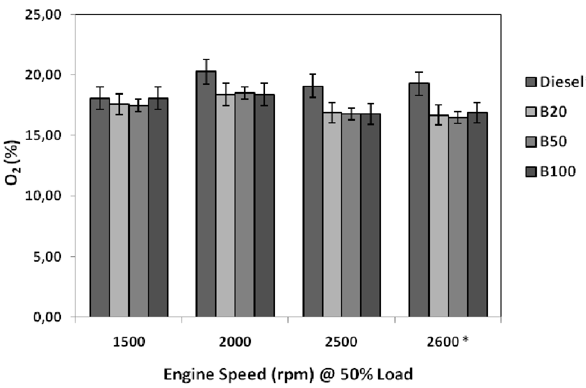


Figure 4. CO_2 concentration with the engine operating at 50%and 75% of full load at various speeds

Despite the available literature (Tickell et al., 2000; Tickell et al., 2006; Feigon, 2003) indicate a considerable reduction in CO_2 emissions when the engine is fueled with biodiesel, our tests show different results: CO_2 emissions of palm oil biodiesel and its blends were higher compared with commercial diesel fuel.

3.3 O_2 Emissions

In a CI diesel engine operating with diesel fuel, approximately 5 to 15% of exhaust emissions are composed of oxygen (Hillier and Coombes, 2004). Figure 5 shows the percentage of O_2 emissions emitted by commercial diesel, palm oil biodiesel (B100) and its blends (B20) and (B50). It can be observed that the O_2 emission from biodiesel and its blends are almost the same, but it is 12% higher for commercial diesel, when compared to the others fuels. This result, combined with the lower CO_2 emission shown previously and the lower NO_X emission shown next, could be due to a more complete combustion scenario for biodiesel blends, although further analysis is necessary.



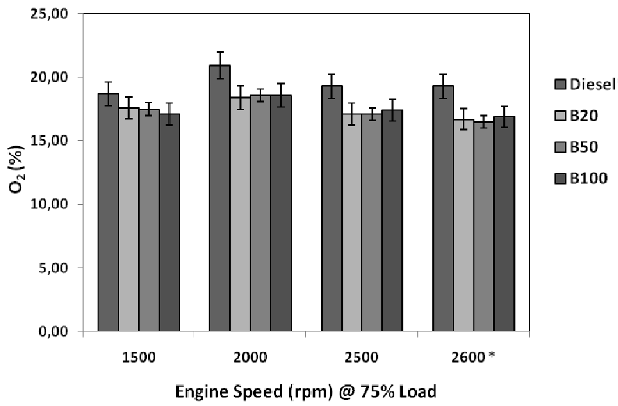
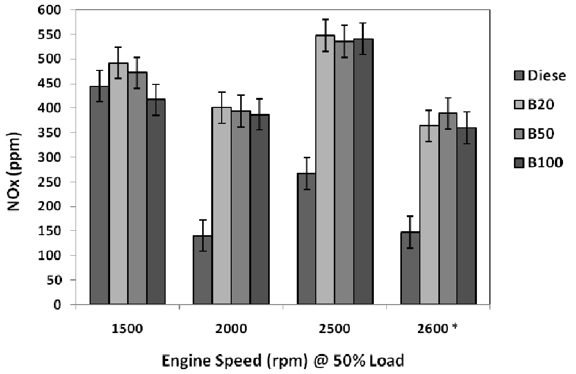


Figure 5. O_2 concentration with the engine operating at 50% and 75% of full load at various speeds

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 and Berg, 2003; Sengupta, 1989; Tickell et al., 2000).

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 et al., 2008). This higher NOx emission from biodiesel fuel is likely due to its higher cetane number, which causes a shorter ignition delay and higher combustion temperatures.



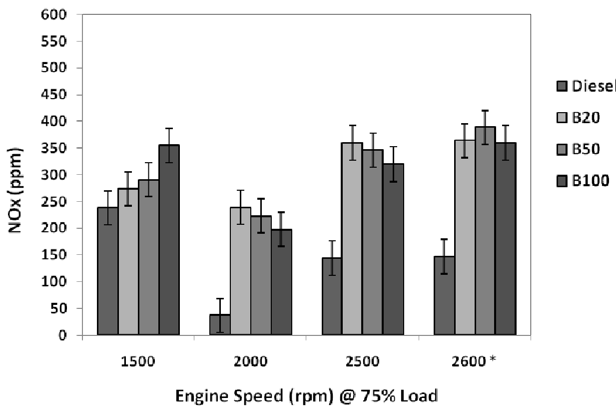
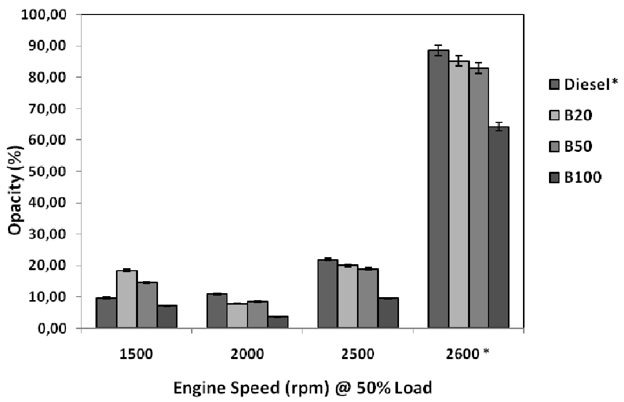
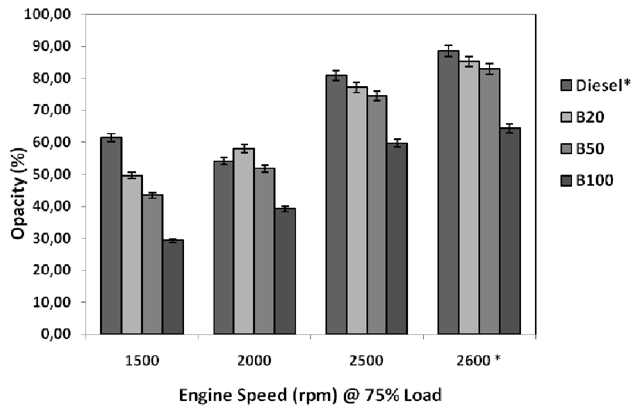


Figure 6. NOx concentration with the engine operating at 50% and 75% of full load at various speeds

3.4 Opacity

Opacity is the amount of soot present in the exhaust stream. It is calculated from the reduction in light transmission through the gases (Kemp, 2006). Hence, it can be considered the percentage of light blocked by smoke emissions (Onursal and Gautam, 1997). Many studies show that smoke opacity is generally lower for biodiesel compared to conventional diesel fuel (Lal and Reddy, 2005). Figure 7 shows that the exhaust gas of commercial diesel fuel contains higher opacity than the one generated by biodiesel and its blends. One can also observe that opacity increases with an increase in either engine speed or load. Opacity decreases as the amount of biodiesel in the mixtures increases because the higher concentration of oxygen in biodiesel aids the soot oxidation process.





speeds

4. ACKNOWLEDGEMENTS

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5. CONCLUSIONS

Test results indicate that the use of commercial diesel fuel leads to the lowest specific fuel consumption, followed by mixtures B20, B50 and, finally, B100. Hence, increasing the percentage of biodiesel in the mixture with commercial diesel causes an increase in specific consumption. At maximum load, the average specific fuel consumption of biodiesel and its blends is 6% higher compared to commercial diesel. This occurs because biodiesel has a smaller heat value than diesel.

The present tests show an increase in NOx emissions. They are partly due to its higher cetane number, which causes a shorter ignition delay and higher combustion temperature. An increase in CO_2 emissions was also observed when the engine is fueled with palm oil biodiesel and its blends in comparison with commercial diesel fuel.

Exhaust gases from commercial diesel fuel contain higher opacity than the ones from biodiesel and its blends. Opacity decreases as the amount of biodiesel in the mixture increases. This occurs because the higher concentration of oxygen in biodiesel aids the soot oxidation process. Longer carbon chains as well as the absence of aromatics and sulfur also contribute to this trend.

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.

6. REFERENCES

Almeida, S. C. A., , Belchior, C. R., Nascimento, M. V. G., Vieira, L. S. R. and Fleury, G., 2002, "Performance of a Diesel generator fuelled with palm oil", Fuel, Vol.81, pp. 2097-102.

ASTM (American Society for Testing and Materials) D6751-07b Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels.

Demirbas, Ayhan, 2008, "Biodiesel: A Realistic Fuel Alternative for Diesel Engines" Ed. Springer, London, England, 208 p.

Demirbas, Ayhan, 2009, "Biofuels: Securing the Planets Future Energy Needs", Ed. Springer, 336 p.

Dorado, M.P., Ballesterosb, E., Arnalc, J. M., Gómez, J. and López, F. J., 2003, "Exhaust Emissions from a Diesel Engine Fueled with Transesterified Waste Olive Oil", Fuel, Vol.82 pp. 1311-1315.

Ellstrand, Norman C., 2005, "Dangerous liaisons?: when cultivated plants mate with their wild relatives", Ed. JHU Press, 264 p.

Faiz A., Weaver C. S. and Michael P., 1996a, "Walsh Air pollution from motor vehicles: standards and technologies for controlling emissions", Ed. World Bank Publications, 246 p.

Faiz, A., Weaver, C. S. and Walsh, M. P., 1996b, "Air Pollution From Motor Vehicles: Standards And Technologies For Controlling Emissions", Ed. World Bank Publications, 246 p.

Feigon, S., United States, Federal Transit Administration, Transit Cooperative Research Program, Transit Development Corporation, National Research Council (U.S.), Transportation Research Board, 2003, "Travel Matters: Mitigating Climate Change with Sustainable Surface Transportation", Ed**.** Transportation Research Board, 59 p.

Gruden, D. and Berg W., 2003, "Traffic and Environment", Ed. Springer, 294 p.

Gunstone, F. D. and Padley, F. B., 1997, "Lipid Technologies and Applications", Ed. CRC Press, 834 p.

Hillier,V. A.W. and Coombes, P., 2004, "Hillier's fundamentals of motor vehicle technology". Ed. Nelson Thornes, 534 p.

Johnston, R. M., Bock, A. E. and Keating, E. L., 1992, "Elements of applied thermodynamics", Ed. Naval Institute Press, 574 p.

Kalam, M.A. and Masjuki, H.H., 2004, "Emissions and deposit characteristics of a small diesel engine when operated on preheated crude palm oil", Biomass and Bioenergy, Vol.27, pp. 289-297.

Kemp W. H., 2006, "Biodiesel: Basics and Beyond (A Comprehensive Guide To Production And Use For The Home And Farm)", Ed. Aztext Press, 588 p.

Kemp, W. H., 2005, "The renewable energy handbook: a guide to rural independence, off-grid and sustainable living", Ed. Aztext Press, 567 p.

Lal B. and Reddy, M. R. V. P., 2005, "Wealth from Waste", Ed. Teri Press, 495 p.

Lapuerta, M., Armas, O. and Fernandez. J. R., 2008, "Effect of Biodiesel Fuels on Diesel Engine Emissions", Progress in Energy and Combustion Science,Vol.34, pp 198–223.

Lin, C.Y. and Lin, H., 2006, "Diesel Engine Performance and Emission Characteristics of Biodiesel Produced by the Peroxidation Process", Fuel, Vol.85, pp. 298-395.

Onursal, B. and Gautam, S., 1997, "Vehicular Air Pollution: Experiences From Seven Latin American Urban Centers". Ed. World Bank Publications, 282 p.

Pahl G. and McKibben. B., 2008, "Biodiesel: Growing a New Energy Economy", Ed.. Chelsea Green Publishing, 368 p.

Peterson, C. L. and Reece, D. L., 1996, " Emissions Testing With Blends of Esters of Rapeseed Oil Fuel with and Without a Catalytic Converter", Society of Automotive Engineers. Paper No. 961114, SAE, Warrendale, Penn.

Rakopoulos, C. D. and Giakoumis, E. G., 2009, "Diesel Engine Transient Operation: Principles of Operation and Simulation Analysis", Ed. Springer, 395 p.

Rakopoulos, C. D., Antonopoulos, K. A., Rakopoulos, D. C., Hountalas, D. T. and Giakoumis, E. G., 2006, "Comparative Performance and Emissions Study of a Direct Injection Diesel Engine Using Blends of Diesel fuel with Vegetable Oils or Biodiesels of Various Origins", Energy Conversion and Management, Vol.47, pp. 3272–3287.

Sengupta, M., 1989, "Mine Environmental Engineering", Ed. CRC Press, 328 p.

Stevens, C. V. and Verhé, R., 2004, "Renewable Bioresources: Scope and Modification for Non-Food Applications", Ed. John Wiley and Sons,. 310p.

Tickell J., Roman K. and Tickell, K., 2000, "From the Fryer to the Fuel Tank: The Complete Guide to Using Vegetable Oil as an Alternative Fuel", Ed. Biodiesel America, 162 p.

Tickell, J., Murphy, M. and Graziano, C., 2006, "Biodiesel America: How to Achieve Energy Security, Free America from Middle-East Oil Dependence, and Make Money Growing Fuel", Ed. Biodiesel America, 340 p.

Wang, W. G., Lyons, D. W., Clark, N. N. and Gautam. M., 2000, "Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification", Environ. Sci. Technol, Vol.34, pp. 933-939.

Zheng, M., Mulenga, M. C., Reader, G. T., Wang M., Ting, D. S. K. and Tjong, J., 2008, "Biodiesel Engine Performance and Emissions in Low Temperature Combustion", Fuel, Vol.87, pp. 714-722.

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